REQ. NO. 1-9082

CONTRACT REPORT NO. OSL81-00344

Recherche sur l'utilisation des poussières de silice pour l'obtention d'un béton à basse teneur en ciment, haute résistance et haute imperméabilité

présenté par le

Dr Pierre Claude Aïtcin

de la Faculté des Sciences Appliquées de
l'Université de Sherbrooke

{Research on the utilization of Silica dust to obtain a low cement Grade in concrete, high resistance and high impermeability.}

MICROMEDIA

OCT 20 1983

68pp.

Prepared under: CANMET Contract
DSS Req. 23440-1-9082

February 1982

PART I

Mechanical Properties and Drying Shrinkage of Condensed Silica Fume Concretes

PROPERTIES OF THE MATERIALS USED IN THE PROJECT

1.1 Fine aggregate Nature: granitic sand from Trois Rivières P.Q.

G_{sss} = 2,63

abs = 0,6%

mf = 2,64

w_{tot} = 2,2%

1.2 Coarse aggregate Nature: metamorphic limestone Lime Ridge P.Q.

G_{sss} = 2,71

ρ_{sss} = 1610 kg/m^3

abs = 0,5%

Composition 20 mm 37,5%

14 mm 37,5% CSA gradation 5-20 mm

10 mm 25%

Chemical composition of the coarse aggregate

Ca O	Si O_2	Al$_2$ O_3	Mg O	Na_2 O	K_2 O	Fe_2 O_3	L.O.I
53,7	1,68	0,5	0,6	0,05	0,10	0,11	43,0

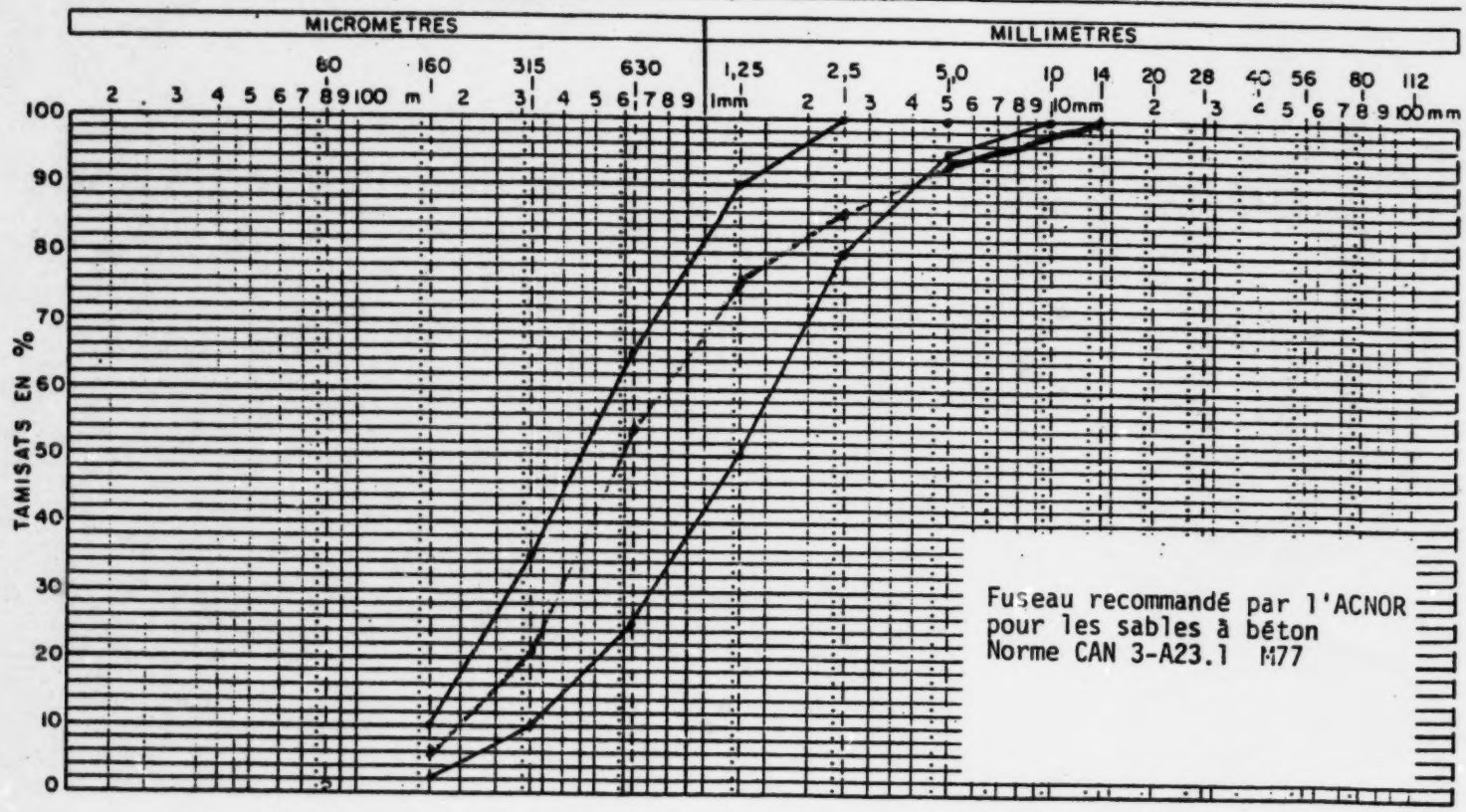
UNIVERSITE DE SHERBROOKE

LABORATOIRE DE MATERIAUX

ANALYSE GRANULOMETRIQUE

PROJET : CANMET SITE Trois Rivières ÉCHANTILLON NO: 1

DESCRIPTION DU GRANULAT : Concrete sand



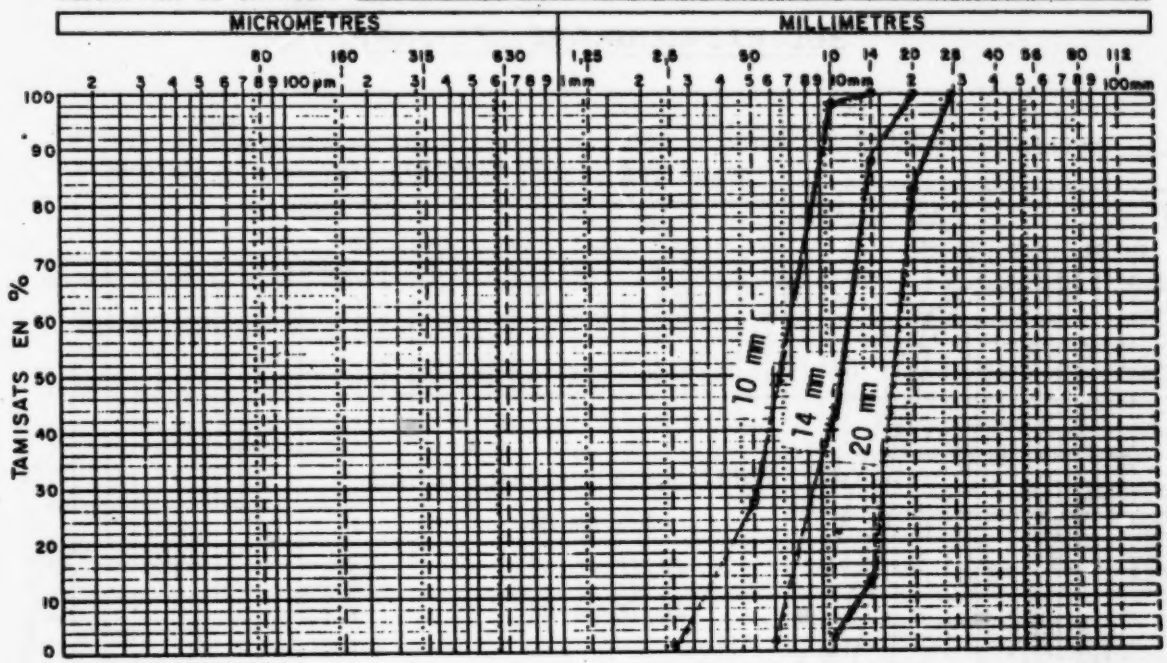
UNIVERSITE DE SHERBROOKE

LABORATOIRE DE MATERIAUX

ANALYSE GRANULOMETRIQUE

PROJET: CANMET SITE: Lime Ridge ECHANTILLON NO: ____

DESCRIPTION DU GRANULAT: coarse aggregates

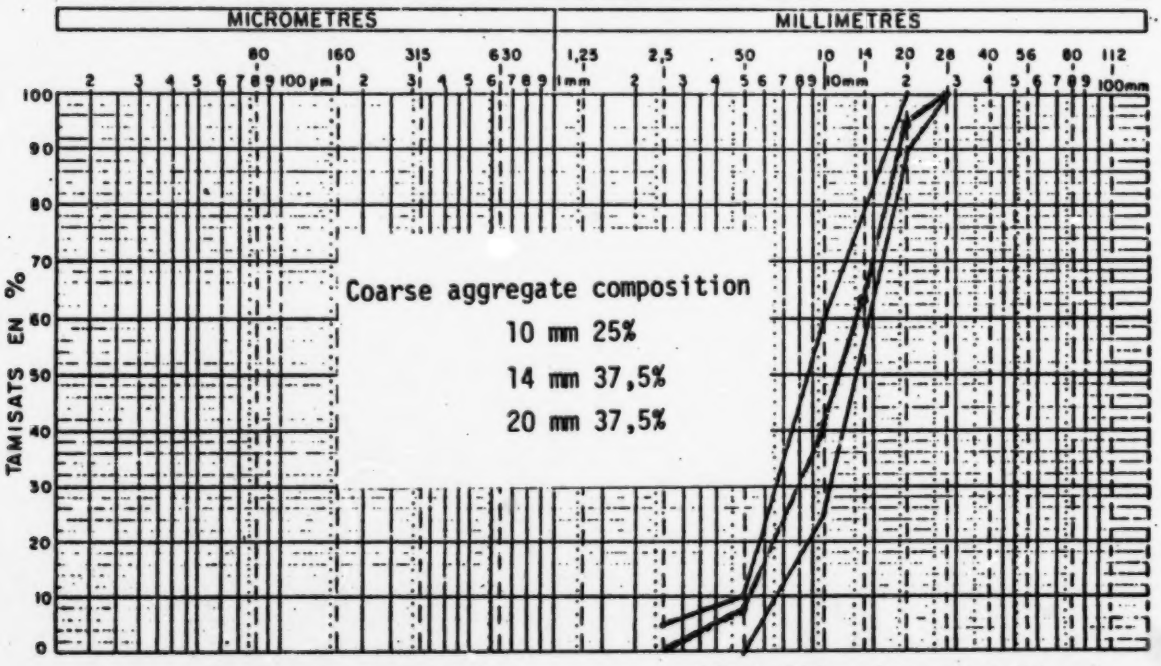


UNIVERSITE DE SHERBROOKE
LABORATOIRE DE MATERIAUX

ANALYSE GRANULOMETRIQUE

PROJET: CANMET SITE: Lime Ridge ECHANTILLON NO: ____

DESCRIPTION DU GRANULAT: concrete coarse aggregate



CAN 3.A23.1 (fuseau 5-20 mm)

1.3 Cement Type 10 Lafarge St Constant plant PQ

Characteristics

setting time	140 mn
% finer 75 µm	95.5%
f'_c 3d	24.1 MPa
7d	29.6 MPa
Blaine	343 m^2/kg

Chemical composition

SiO_2	Al_2O_3	Fe_2O_3	CaO total	CaO free	MgO	L.O.I.	insoluble
21,2	4,1	2,7	63,4	0,7	3,0	0,9	0,2

Bogue Composition

$C_3A = 6,4\%$ $C_3S = 53,8\%$ $C_2S = 20,2\%$ $C_4AF = 8,2\%$

1.4 Condensed Silica Fume (C.S.F.) From SKW Canada Bécancour P.Q.

SiO_2	Al_2O_3	Fe_2O_3	C_aO	MgO	Alkalis	C	L.O.I.
93,6	0,3	0,5	0,3	0,5	1,4	1,9	2,8

This C.S.F. was produced during the fabrication of silicon because of the low iron oxide and high silica contents.

specific gravity 2,20

1.5 Additives

. Air entraining Agent Darex from GRACE (ASTM-C-260)

. Superplasticizer Mighty 150 from Atlas Chemical

2. TESTING PROGRAM

As requested 2 cement dosages have been used 175 and 235 kg of cement/m^3 (300 and 400 lb/cu. yd. respectively) corresponding to the program A and B of the contract.

For each cement dosage 4 different types of concrete were made. The first one was a plain concrete containing no C.S.F. used as a reference and the 3 others contained 10, 15, 20% of C.S.F.

	Percentage of C.S.F.			
Program and cement dosage	0%	10%	15%	20%
Program A 175 kg/m^3	X	X	X	X
Program B 235 kg/m^3	X	X	X	X

The air content was kept constant in between 5 to 7%. The slump was kept constant in between 75 to 85 mm. When C.S.F. was added in the mix a certain amount of Mighty 150 was added to maintain the slump at the same level.

In each case 4 different concrete batches were made and used as follow.

1st batch

Fifteenth 100 x 200 specimens were cast for compressive strength measurements at 1 d, 7 d, 28 d, 91 d and 1 year. (3 specimens each time).

2nd batch

Four 100 x 200 specimens for 28 d compressive strength
Four 150 x 300 specimens for Elastic Modulus measurements.

3rd batch

Three 100 x 200 specimens for 28 d compressive strength
Four prisms 75 x 75 x 380 for shrinkage measurement after 3 and 28 d of water curing (2 each time)
One 150 x 125 x 225 mm block for porosity and permeability measurements.

4th batch

Four 100 x 200 specimens for compressive strength at 28 d
Six prisms 75 x 75 x 380 for M.O.R. measurements at 14 and 28 d (3 each time).

3. PRESENTATION OF THE RESULTS

The composition and properties of the 32 mixes that have been made are given in a unique table presented in appendix. All the results have been presented in the Figures 1 to 19 and will be discussed in the following. However the main results have been summarized in the Tables 1 and 2 and will be discussed briefly.

3.1 Discussion of Tables 1 and 2.

3.1.1 Compressive strength at 28 d

The addition of C.S.F. to the mix (combined with the use of a superplasticizer) increase greatly the compressive strength of the concrete. The first 10% addition of C.S.F. practically double the compressive strength at 28 d. However, a 10% more addition of C.S.F. (total dosage of C.S.F. = 20%) is producing only a very limited additional strength increase.

As C.S.F is available only in limited amount and therefore should not be wasted it should be interesting to find the most efficient dosage of C.S.F. in concrete as far as the compressive strength is concerned.

The two concretes A-10% and B-0% are equivalent as far as their compressive strength is concerned.

3.1.2 M.O.R.

The M.O.R. increases with the dosage of C.S.F. but not as significantly as the compressive strength. The M.O.R. of the concretes A-10% and B-0% are the same as the compressive strengths were.

3.1.3 Young modulus

The young modulus increases with the dosage of C.S.F.

3.2 Efficiency of the C.S.F.

Comparing the 28 d compressive strength of the reference concrete of the program B and the compressive strength of the concrete containing 10% C.S.F. of the program A in Tables 1 and 2 it can be seen that these two concretes are more or less equivalent

Program A - 10% 22 MPa
Program B - 0% 22.2 MPa

In the reference concrete of program B 235 kg of cement were used. This amount of cement has produced the same 28 d compressive strength as the 175 kg of cement and 17.5 kg of C.S.F. of the concrete A-10%.

So the 17.5 kg of C.S.F. have produced the same strength increase as 237-175 = 62 kg of cement. The cement equivalent of the C.S.F. is

$$C.E = \frac{62}{17.5} = 3.5 \text{ kg of cement/kg of C.S.F.}$$

NOTE: If reference concretes having compressive strength up to 50 MPa are added to a following program it will be possible to calculate the cement equivalent of the C.S.F. for the 5 other mixes containing C.S.F.

TABLE 1
PROGRAM A

SiO_2%		0	10	15	20
water	kg/m³	175	175	175.5	175
cement		175	175	175	175
coarse		986	984	993	987
fine		927	926	945	925
Darex cm^3/m^3		67	95	111	137
Mighty L/m^3		0	1.0	1.0	0.9
slump mm		78	84	76	75
air %		6.4	6.3	5.8	6.0
sp.w.kg/m^3		2264	2278	2315	2296
$E/C+SiO_2$		1.00	0.91	0.87	0.83
f'_c 28 d MPa		10.7	22.0	24.4	26.8
M.O.R MPa		2.6	4.0	3.8	4.0
E GPa		23.6	30.2	31.0	33.0

PROGRAM B

SiO_2 %		0	10	15	20
water	kg/m³	161	163	159	160
cement	kg/m³	237	238	235	236
coarse	kg/m³	1042	1045	1035	1037
fine	kg/m³	872	867	859	860
Darex cm^3/m^3		64	124	150	189
Mighty L/m^3		0	1.2	1.9	2.3
slump mm		74	76	80	78
air %		6.4	5.9	5.9	5.8
sp.w.kg/m^3		2311	2334	2323	2340
E/C+SiO_2		0.68	0.62	0.59	0.57
f'_c 28 d MPa		22.2	39.9	42.3	46.2
M.O.R. MPa		4.1	5.0	5.6	6.0
E GPa		31.4	32.7	34.2	34.6

4. DISCUSSION OF THE RESULTS OBTAINED ON FRESH CONCRETE

4.1 Dosage of the air entraining agent A.E.A. as a function of the C.S.F. content

As can be seen in Figure 1 when C.S.F. is introduced in the mix the A.E.A. dosage has to be increased significantly to keep the air content constant. The higher the silica fume content the higher the A.E.A. dosage. For the program B the dosage of the A.E.A. was 3 times higher when 20% of C.S.F. was added in the mix.

4.2 Dosage of the superplasticizer used to keep a constant slump as a function of C.S.F. content

As can be seen in Figure 2 the amount of superplasticizer necessary to maintain a constant slump in the mix increases with the amount of C.S.F. in the mix. In the program B a dosage of $3L/m^3$ was necessary to maintain a constant slump when 20% of C.S.F. was added in the mix.

4.3 Unit weight of the fresh concrete as a function of the air content

As can be seen in Figure 3 the air content of most of the mixes was kept within the specification except for 2 mixes; one having a 4.6% air content and the other a 7 4 air content.

The unit weight of the fresh concrete is varying linearly with the amount of air present in the concrete as usual. The unit weight of the richer mix being higher than that of the leaner mix. These results are quite normal.

5. DISCUSSION OF THE RESULTS OBTAINED ON HARDENED CONCRETE

5.1 Unit weight of the hardened concrete as a function of the air content

The unit weight of all the cores that have been submitted to the permeability test has been measured and the results reported in Figure 4. Here also it can be seen that the unit weight of the hardened concrete varies linearly with the amount of air contained in the concrete, but but it seems than the two lines are no more parallels like for the fresh concrete.

5.2 Compressive strength of the concrete of program A and B

These results have been plotted in two different ways using an arithmetic scale for the age of testing in Figures 5 and 7, and a logarithmic scale in Figures 6 and 8. The only advantage of the logarithmic scale is that this type of presentation shows very clearly when the C.S.F. is really active in the mix.

For both program A and B the 3 d compressive strength is practically not affected by the introduction of the additional C.S.F. in the mix, most of the compressive strength of the mix is still given by the cement. But at 7 d it can be seen than the C.S.F. has started to react with the lime liberated during the hydration of the cement and so far increases significantly the compressive strength of the different concretes. At 28 d the strength increases are more significant.

5.3 Compressive strength as a function of the C.S.F. content

As can be seen in Figures 9 and 10 the higher the C.S.F. content the higher the strength increase, but this increase of the compressive strength is not proportional to the amount of C.S.F. introduced in the mix. As can be seen in these 2 Figures the first 10% of C.S.F. introduced in the mix is much more active than the 5 and 10% following additions.

So there exist an optimum dosage of C.S.F. where the C.S.F. is giving the highest compressive strength increase in regard to the amount of C.S.F. introduced in the mix. As C.S.F. will be available in limited amount it should be interesting to define exactly what is this optimum dosage, in order to be sure to use C.S.F. in the most efficient way.

5.4 Modulus of rupture as a function of the C.S.F. content

As can be seen in Figure 11 the M.O.R. is increasing with the C.S.F. content, but more significantly at 28 d than at 14 d probably because at 28 d the C.S.F. has had enough time to develop its pozzolanic reaction. However the M.O.R. increases are less spectacular than the ones observed on the compressive strength.

5.5 Modulus of rupture as a function of the compressive strength

As can be seen in Figure 12 the M.O.R. is increasing with the compressive strength as in an ordinary concrete.

The results presented in this Figure 12 are confined within 2 parallel lines and are very consistant.

5.6 Stress/strain curves

The stress/strain curves used to determine the modulus of elasticity of the different concretes have been plotted in Figure 13 for program A and 14 for program B. From these two curves it can be seen that the elastic modulus is increasing with the amount of C.S.F. in the mix but more significantly in the program A than in the program B. As the reference concrete in program A was very lean the C.S.F. has greatly increased the compacity of the concrete structure, the first 10% addition of C.S.F. being the most effective in that respect.

It can be noted than the mixes A-10% and B-0% which has already the same compressive strength and the same M.O.R. have practically the same modulus of elasticity 30.2 GPa for A-10% and 31.4 for B-0%. These two concretes can actually be considered as equivalent from a design point of view as far as their mechanical properties are concerned.

5.7 Modulus of elasticity as a function of the compressive strength

As can be seen in Figure 15 the modulus of elasticity of the concretes that were containing C.S.F. seems to be less related to the compressive strength than in the case of the

plain concrete.

In this Figure the theoretical relation given by the A.C.I. $E_c = 4\,730\ (\sigma'_c)^{\frac{1}{2}}$ GPa has been plotted as a reference curve. The compressive strength of the 2 plain concretes were significantly higher than their theoretical values, this is probably related to the nature of the coarse aggregate used in the mix. This metamorphic limestone has a quite low modulus of elasticity for a concrete aggregate, E = 50 GPa, not far from that of the hydrated cement paste as it has been pointed out in a research done in our laboratory on very high strength concrete.

5.8 Drying shrinkage curves

Two series of measurement have been made as requested in the research contract. The first serie of measurements was done after 3 d of water curing when the C.S.F. ha not enough time to totally develop its pozzolanic reaction. The second one was done after 28 d of water curing when most of the pozzolanic reaction of the C.S.F. has been achieved. The results for program A and B have been plotted in Figure 16 to 19 for both programs and both water curing period.

5.8.1 3 d of wet curing - 175 kg/m^3 Program A (Figure 16)

There is at the beginning a slight expansion then all the samples shrink. The shrinkage is increasing with the C.S.F. content in the mix. After 50 days it seems that the total shrinkage is starting to stabilize.

5.8.2 3 d of wet curing - 235 kg/m^3 Program B (Figure 17)

The first expansion period is shorter than in the preceeding case. The shrinkage is also increasing with the C.S.F. content in the mix, but does not seems to be stabilized after 50 d of dry curing.

5.8.3 28 d of wet curing - 175 kg/m^3 Program A (Figure 18)

There is also a first period when some expansion is noted, this period is shorter for the mixes containing C.S.F. than for the reference mix. The total shrinkage is about half the one measure for 3 d of wet curing moreover it increases with the C.S.F. content.

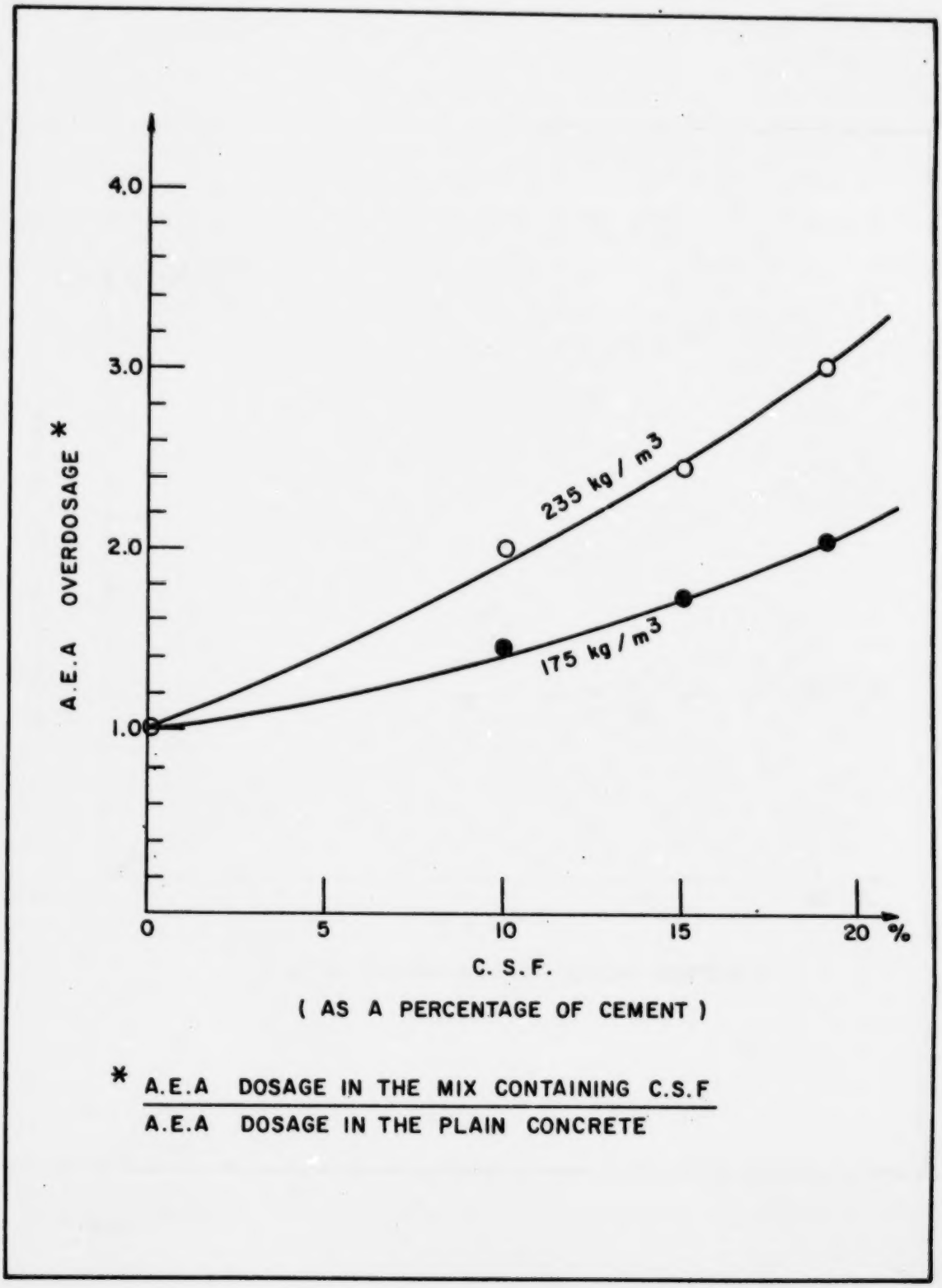
5.8.4 28 d of wet curing - 235 kg/m^3 Program B (Figure 19)

There is practically no more expansion at the beginning of the dry curing. The shrinkage increases with the C.S.F. content but in that case it has been slightly lower than that of the reference concrete.

5.8.5 Conclusion

It can be concluded that:

- generally a concrete containing C.S.F. shrinks a little bit more than a plain concrete
- the shrinkage is increasing with the C.S.F. content of the mix
- the shrinkage is more pronounced when the wet curing is very short



* A.E.A DOSAGE IN THE MIX CONTAINING C.S.F / A.E.A DOSAGE IN THE PLAIN CONCRETE

Figure 1

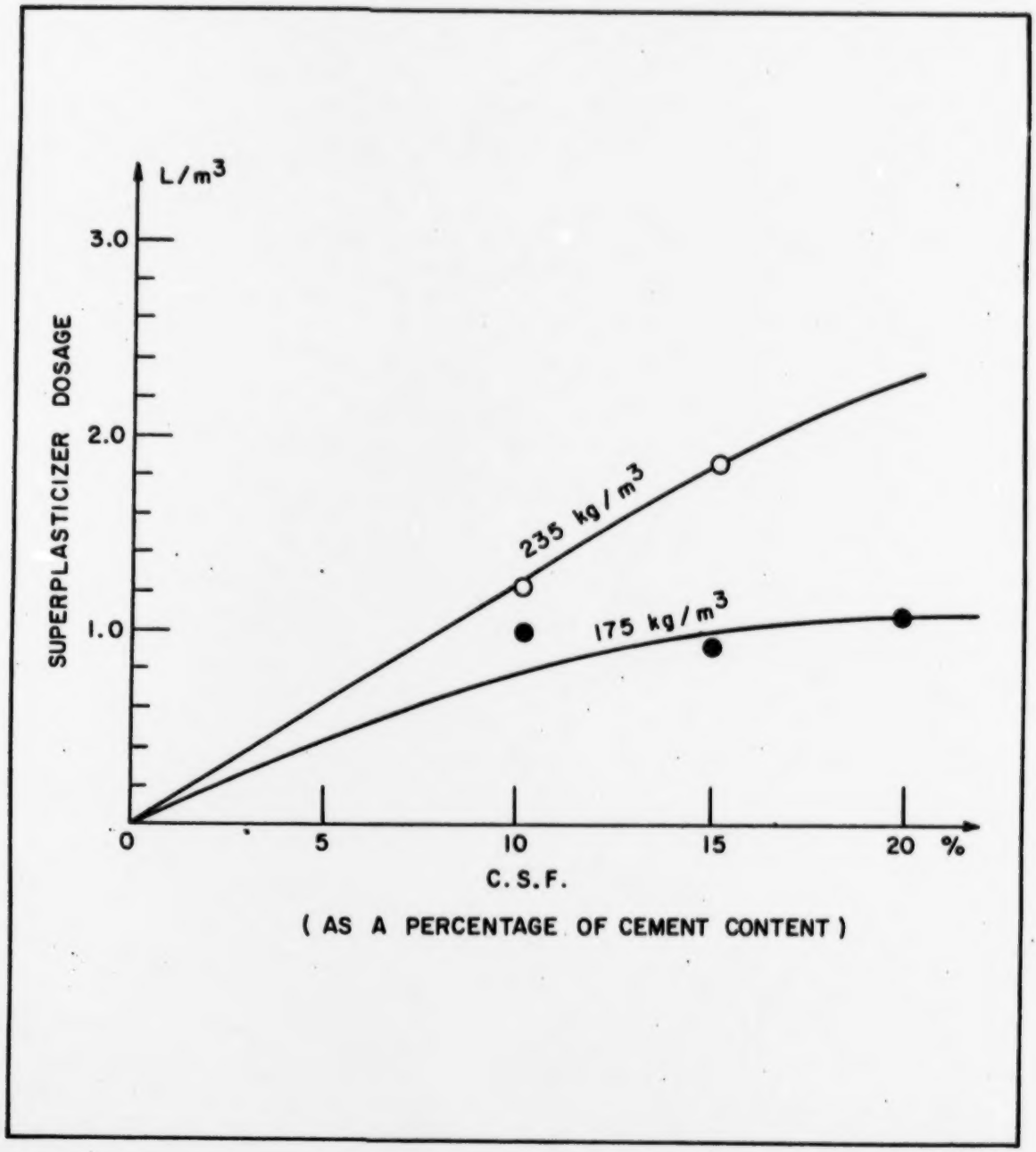

L/m3
3.0
2.0
1.0
SUPERPLASTICIZER DOSAGE
235 kg/m3
175 kg/m3
0
5
10
15
20
%
C.S.F.
(AS A PERCENTAGE OF CEMENT CONTENT)

Figure 2

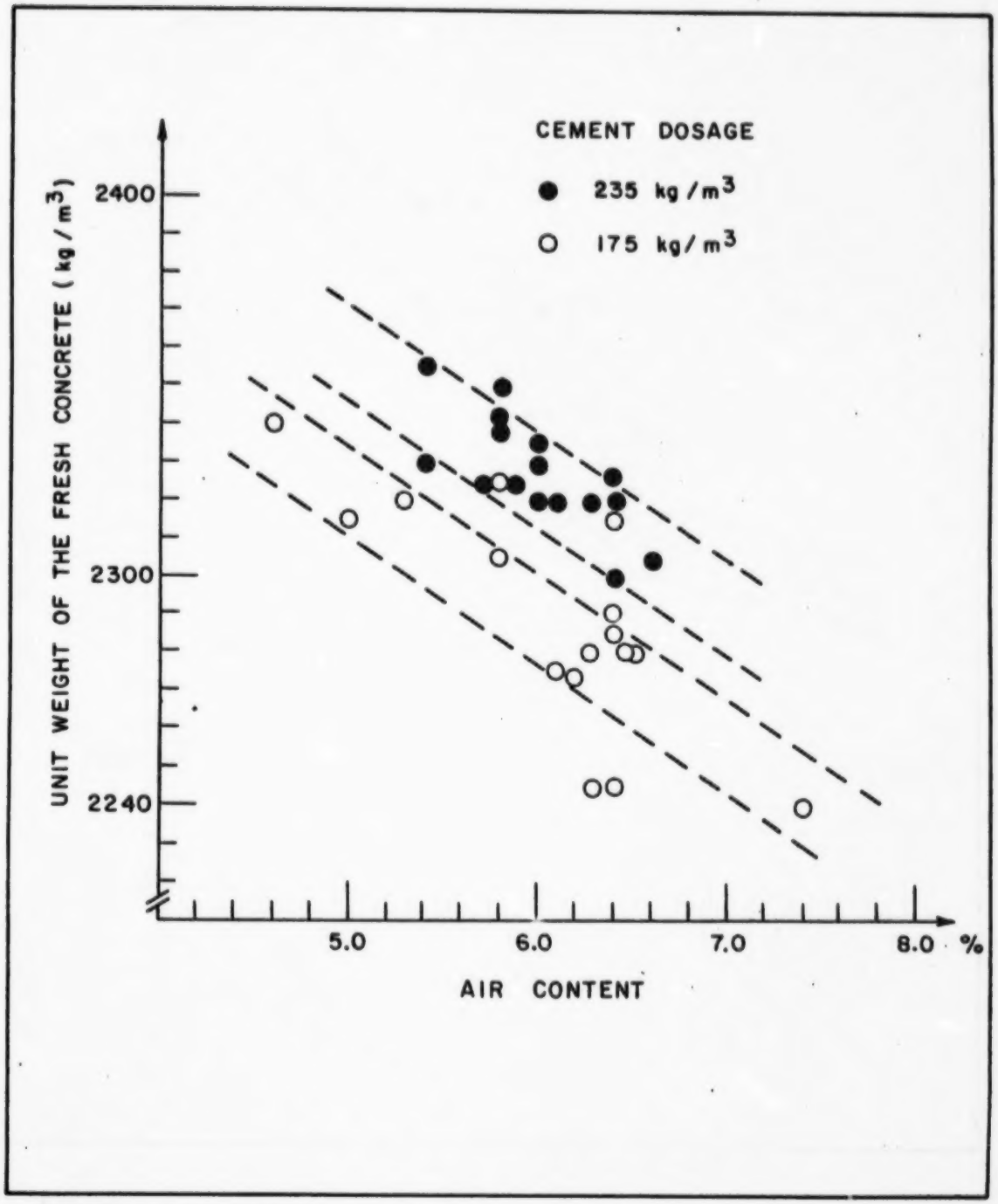

CEMENT DOSAGE
● 235 kg/m3
○ 175 kg/m3
UNIT WEIGHT OF THE FRESH CONCRETE (kg / m3)
2400
2300
2240
5.0
6.0
7.0
8.0 %
AIR CONTENT

Figure 3

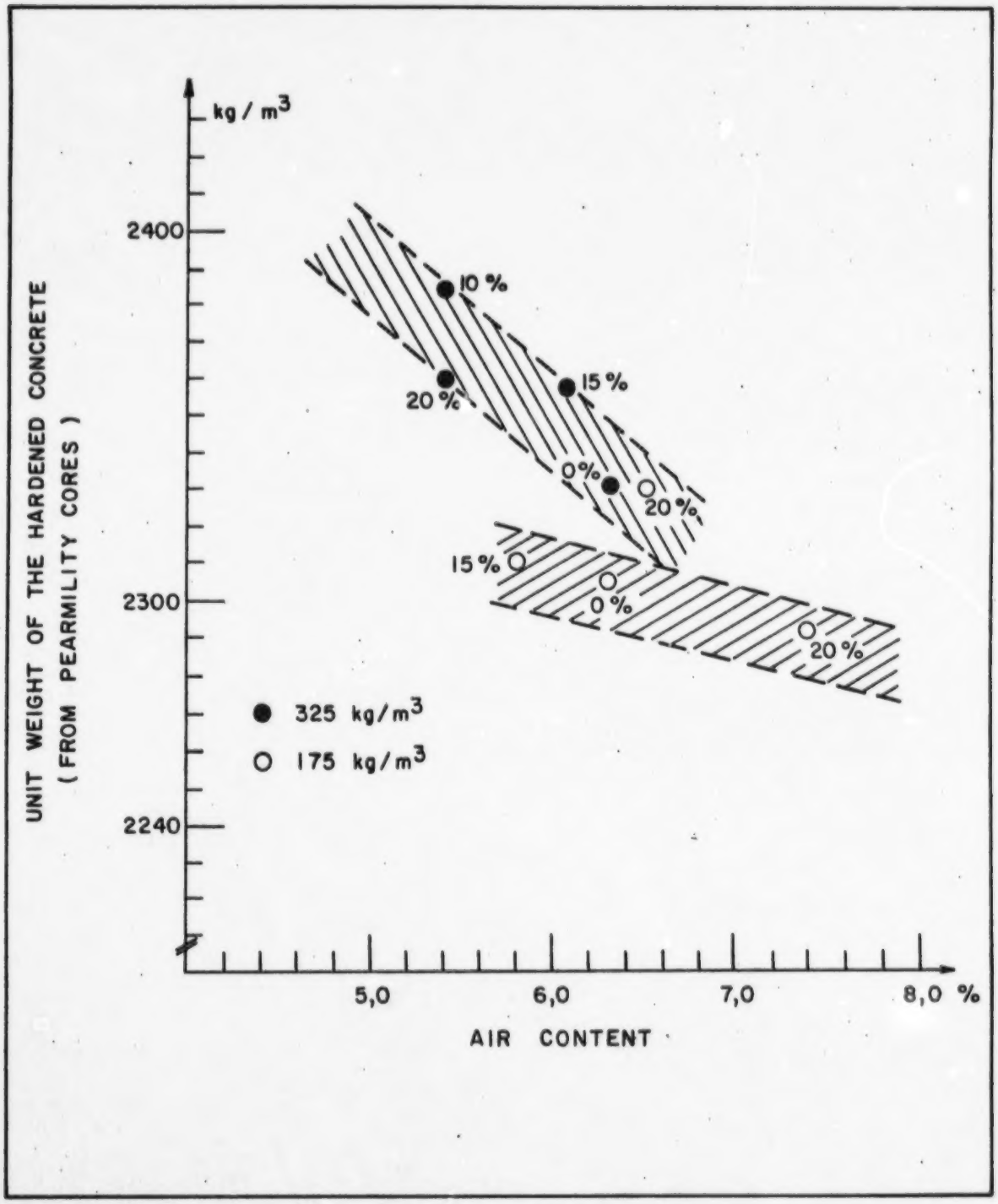

kg / m3
2400
2300
2240
UNIT WEIGHT OF THE HARDENED CONCRETE
(FROM PEARMILITY CORES)
10 %
15 %
20 %
0%
20 %
15 %
0 %
20 %
325 kg/m3
175 kg/m3
5,0
6,0
7,0
8,0 %
AIR CONTENT

Figure 4

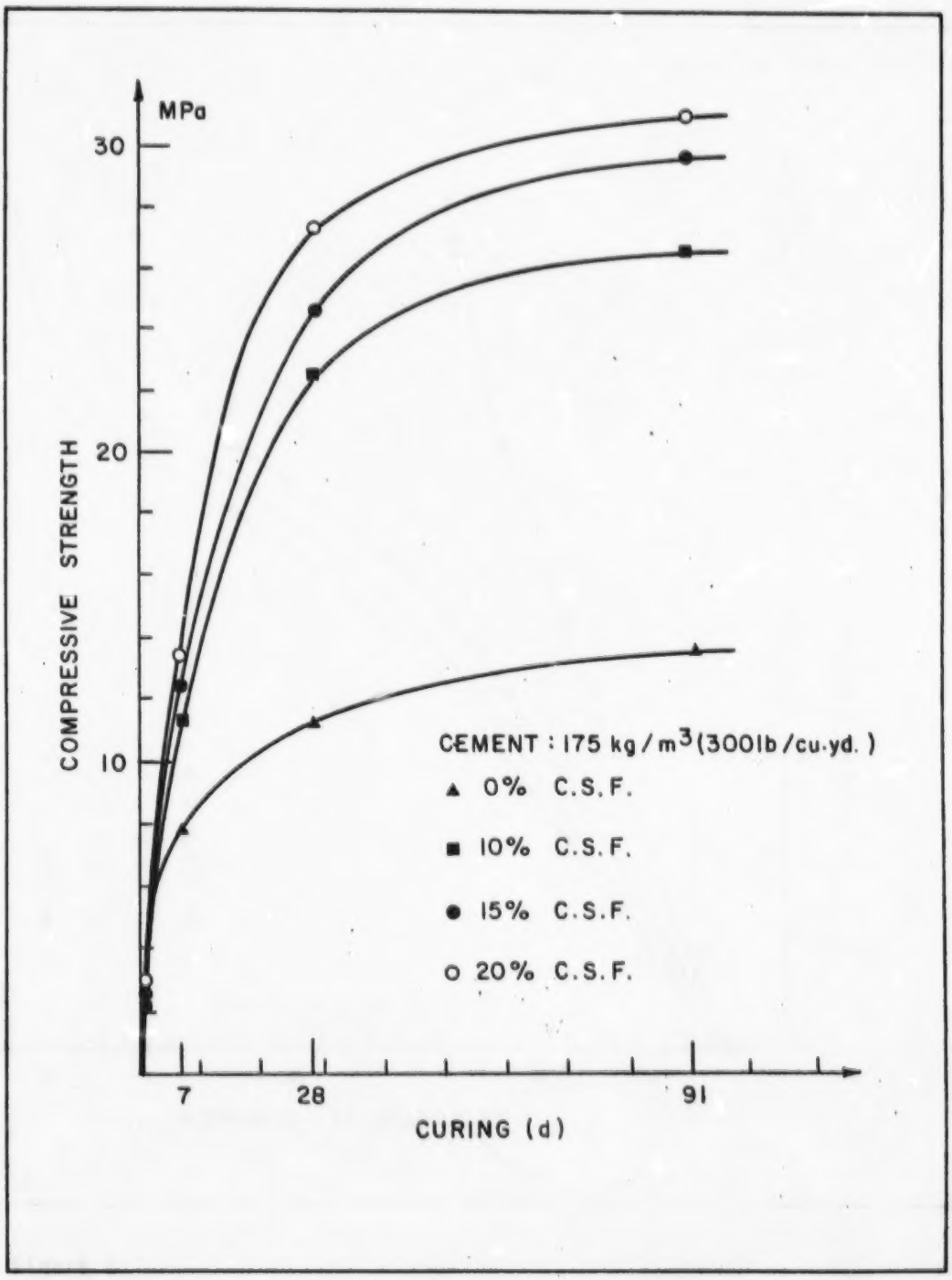

MPa
30
20
10
COMPRESSIVE STRENGTH
CEMENT : 175 kg / m3 (300lb / cu.yd.)
▲ 0% C.S.F.
■ 10% C.S.F.
● 15% C.S.F.
○ 20% C.S.F.
7
28
91
CURING (d)

Figure 5

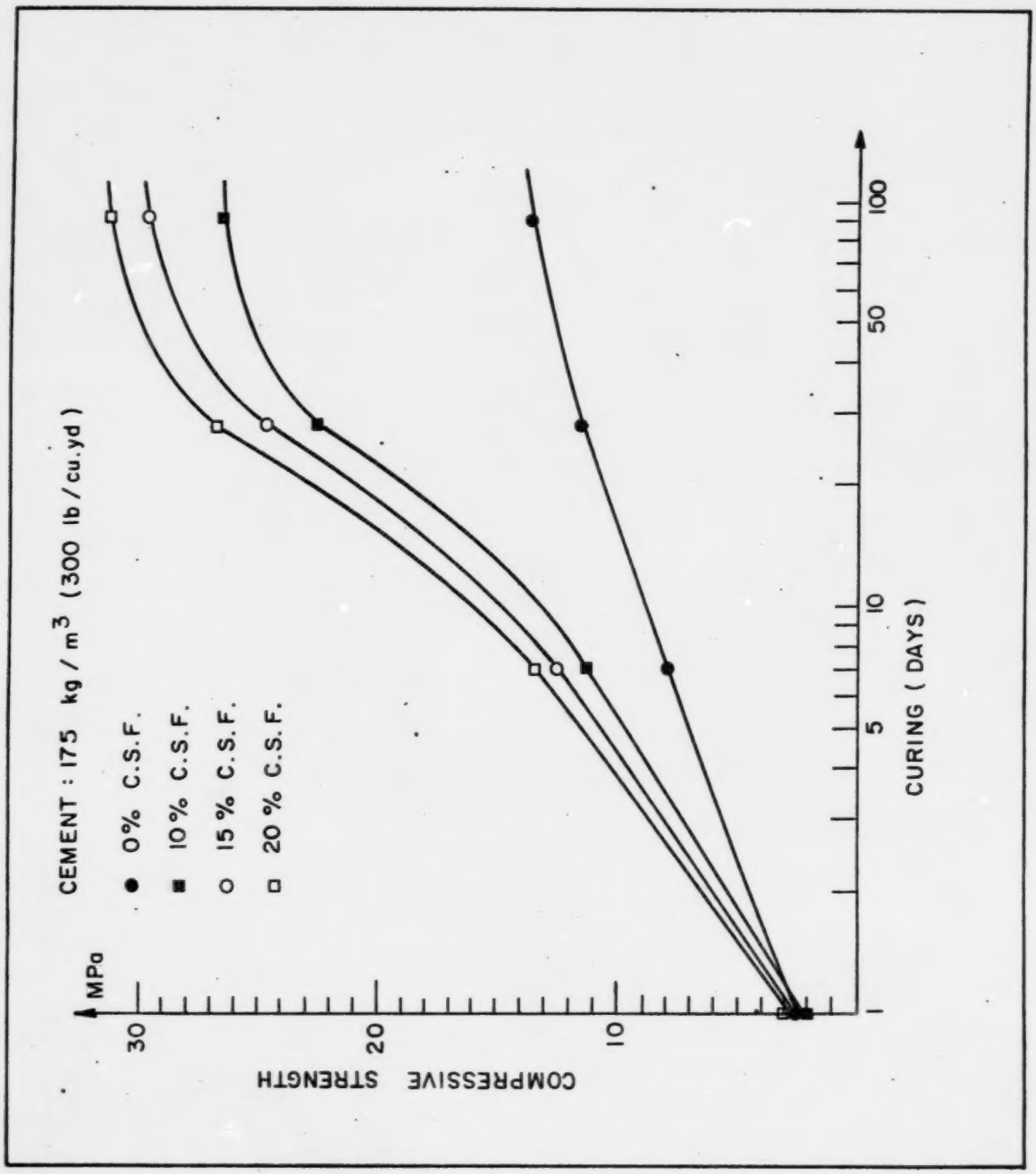

CEMENT : 175 kg / m3 (300 lb / cu.yd)
● 0% C.S.F.
■ 10% C.S.F.
○ 15% C.S.F.
□ 20% C.S.F.
MPa
30
20
10
COMPRESSIVE STRENGTH
1
5
10
50
100
CURING (DAYS)

Figure 6

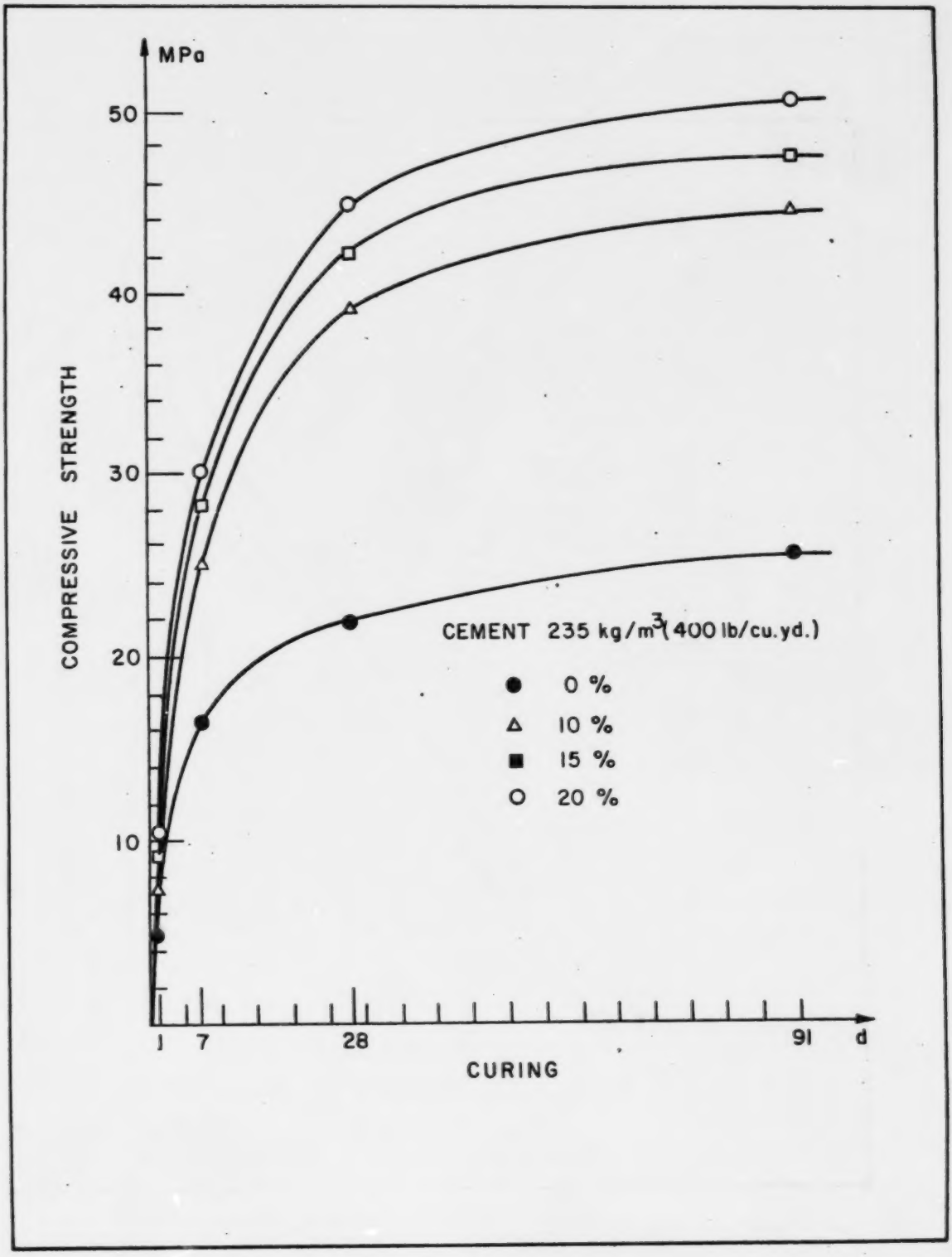

MPa
50
40
30
20
10
COMPRESSIVE STRENGTH
CEMENT 235 kg/m³ (400 lb/cu.yd.)
0 %
10 %
15 %
20 %
1
7
28
91
d
CURING

Figure 7

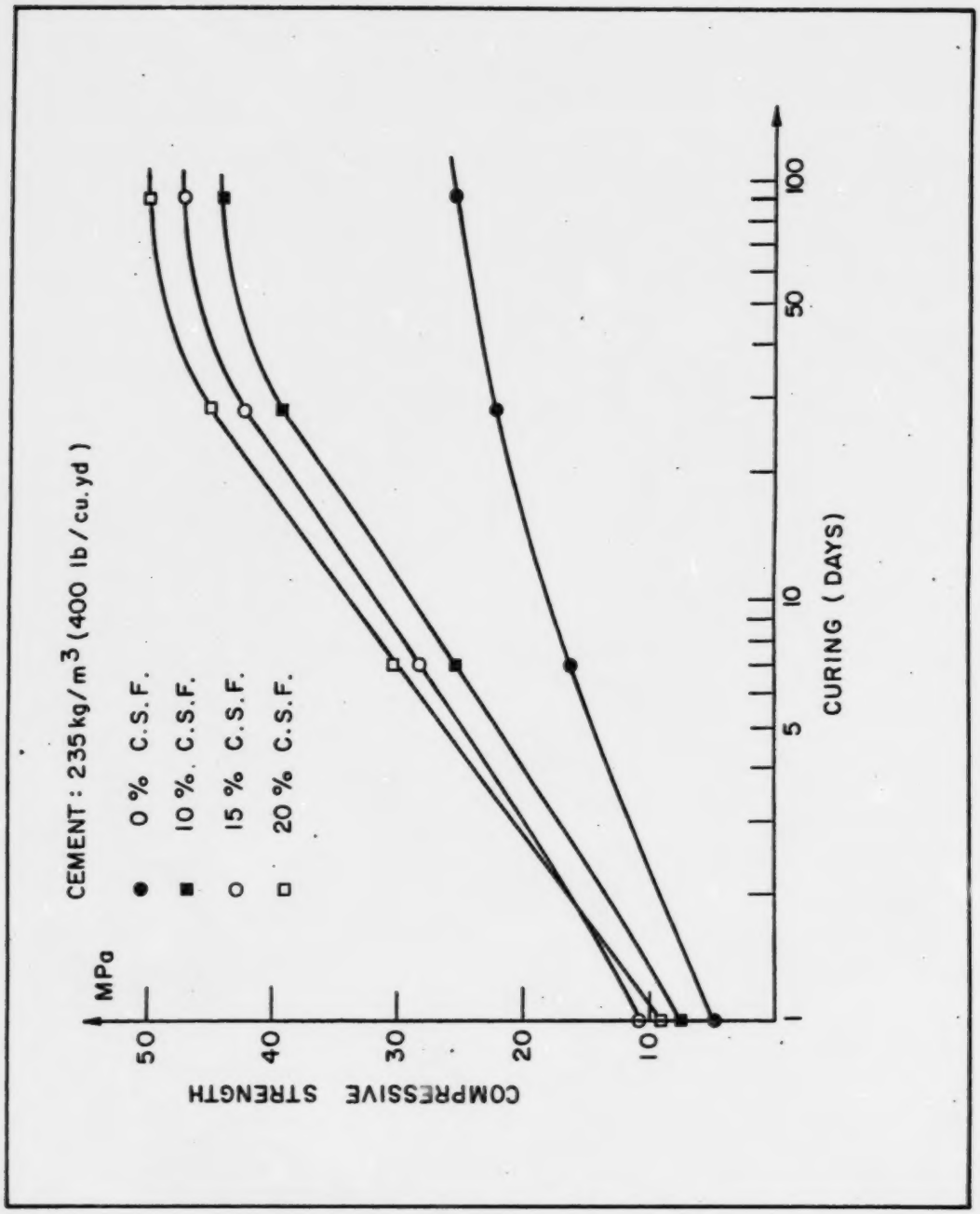

CEMENT : 235 kg/m3 (400 lb / cu.yd)
0 % C.S.F.
10 % C.S.F.
15 % C.S.F.
20 % C.S.F.
MPa
50
40
30
20
10
COMPRESSIVE STRENGTH
1
5
10
50
100
CURING (DAYS)

Figure 8

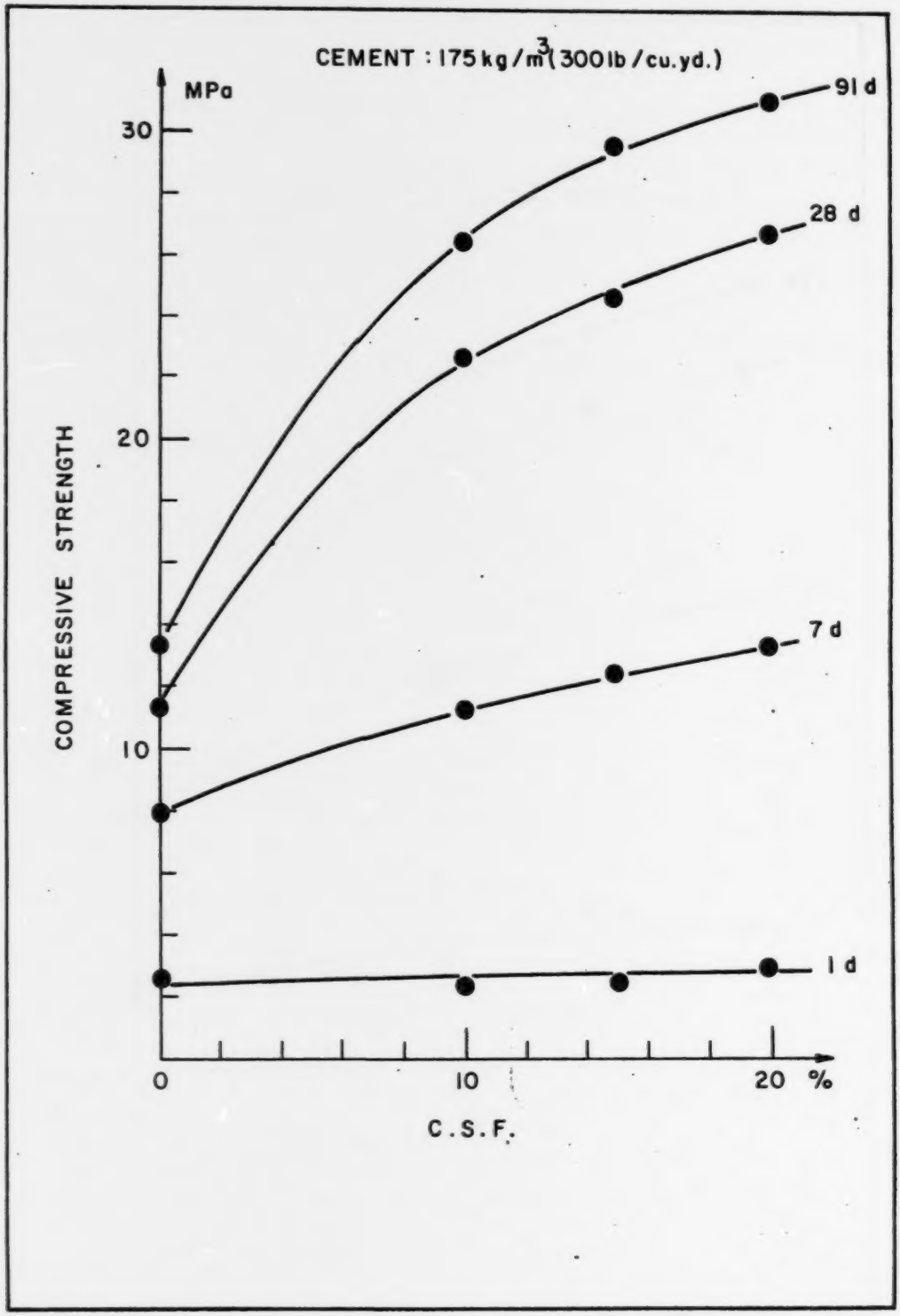

CEMENT : 175 kg / m³ (300 lb / cu.yd.)
MPa
30
20
10
COMPRESSIVE STRENGTH
91 d
28 d
7 d
1 d
0
10
20 %
C.S.F.

Figure 9

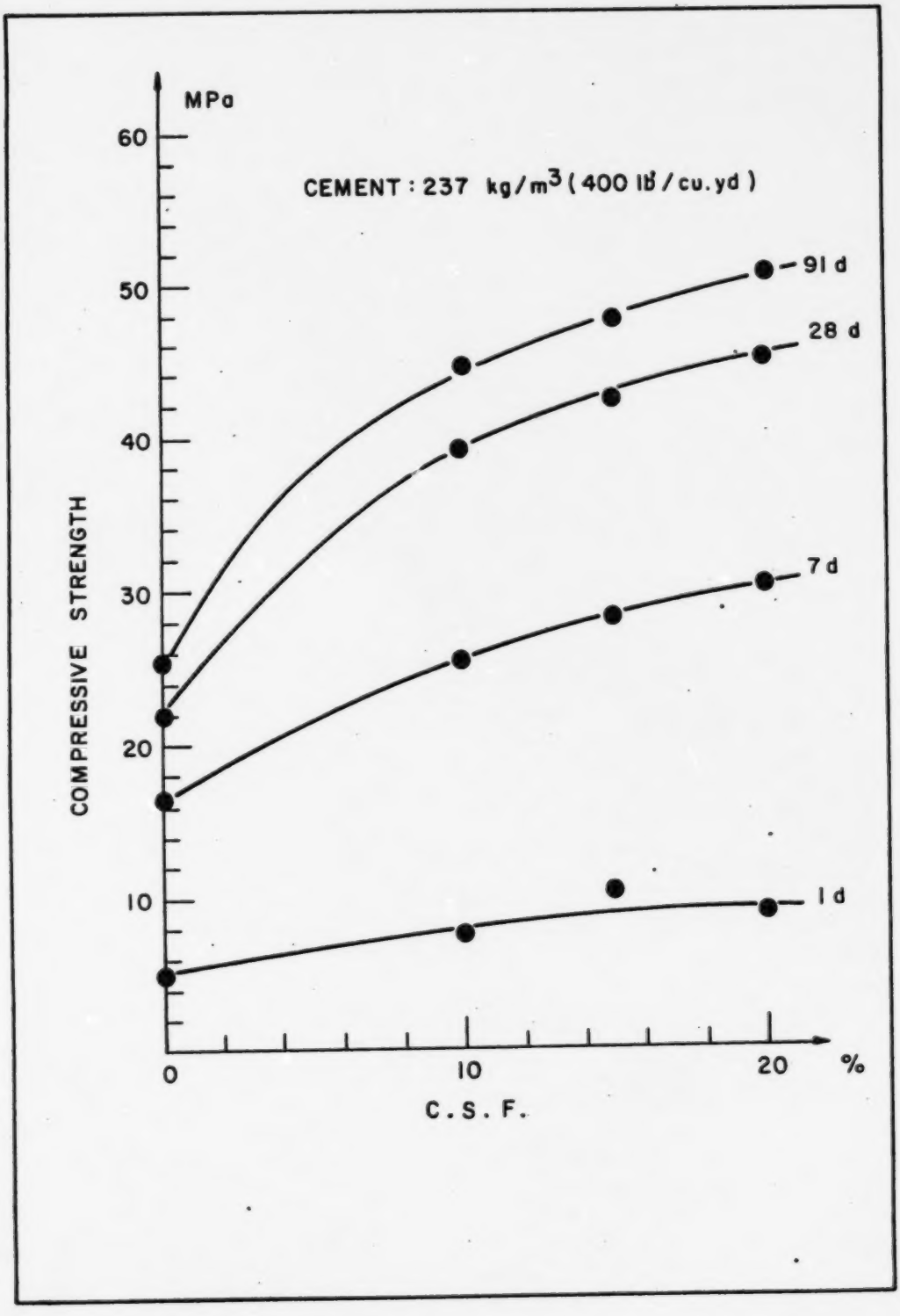

MPa
60
50
40
30
20
10
CEMENT : 237 kg/m3 (400 lb / cu.yd)
91 d
28 d
7 d
1 d
COMPRESSIVE STRENGTH
0
10
20
%
C.S.F.

Figure 10

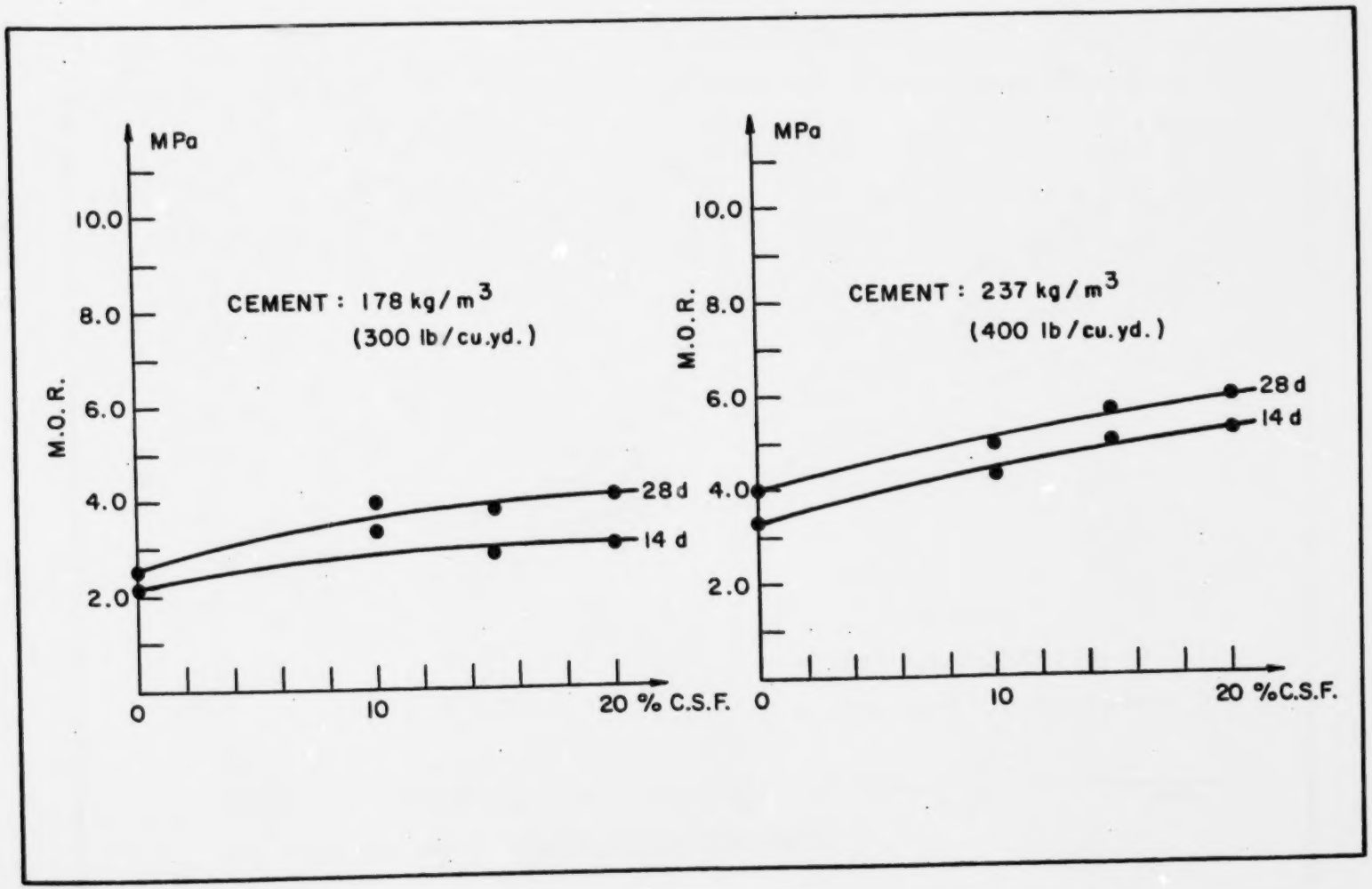

MPa
10.0
8.0
6.0
4.0
2.0
M.O.R.
CEMENT : 178 kg/m3
(300 lb/cu.yd.)
28 d
14 d
0
10
20 % C.S.F.
MPa
10.0
8.0
6.0
4.0
2.0
M.O.R.
CEMENT : 237 kg/m3
(400 lb/cu.yd.)
28 d
14 d
0
10
20 %C.S.F.

Figure 11

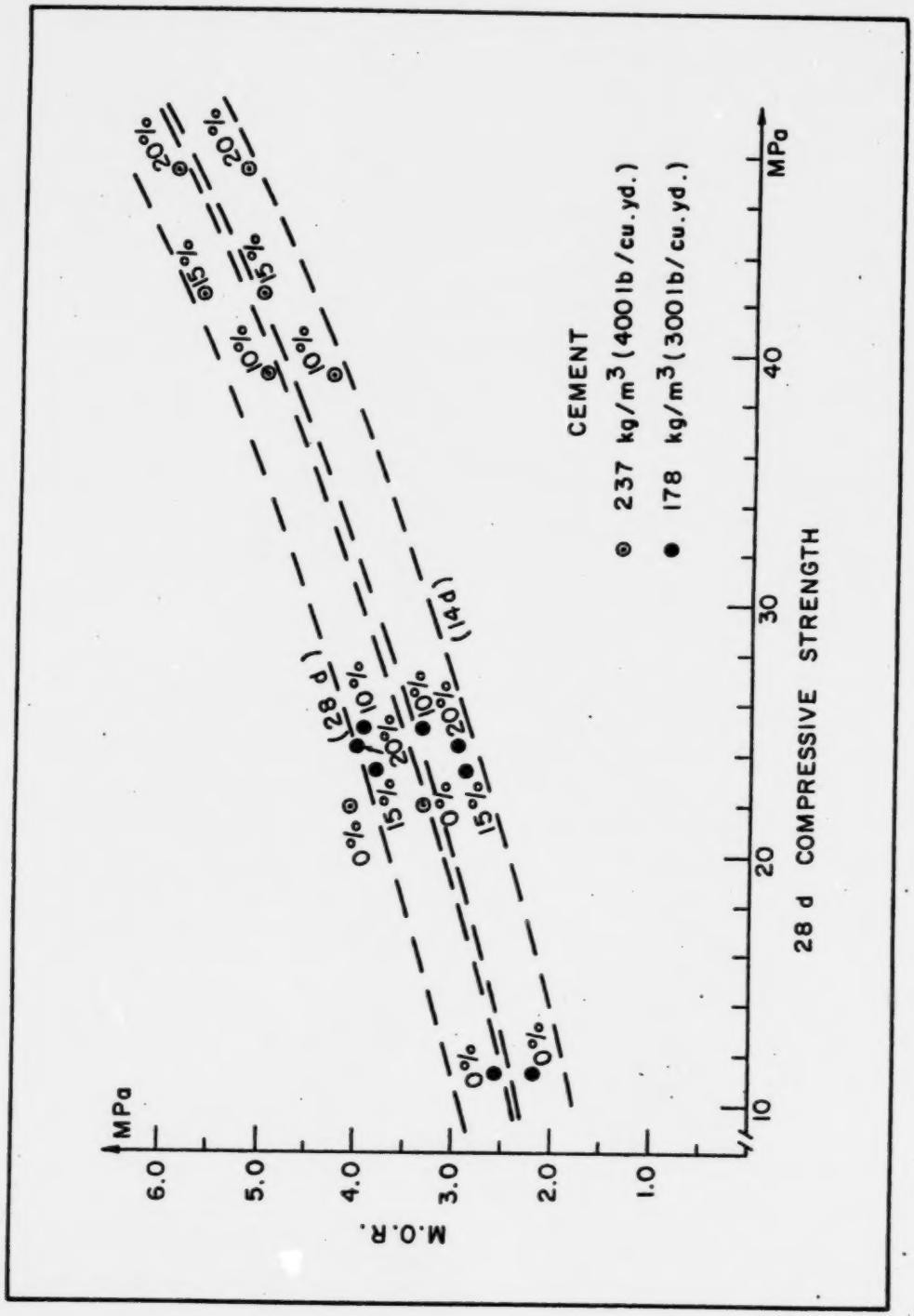

MPa
6.0
5.0
4.0
3.0
2.0
1.0
M.O.R.
10
20
30
40
MPa
28 d COMPRESSIVE STRENGTH
CEMENT
237 kg/m³ (400 lb/cu.yd.)
178 kg/m³ (300 lb/cu.yd.)
0%
10%
15%
20%
(28 d)
(14 d)

Figure 12

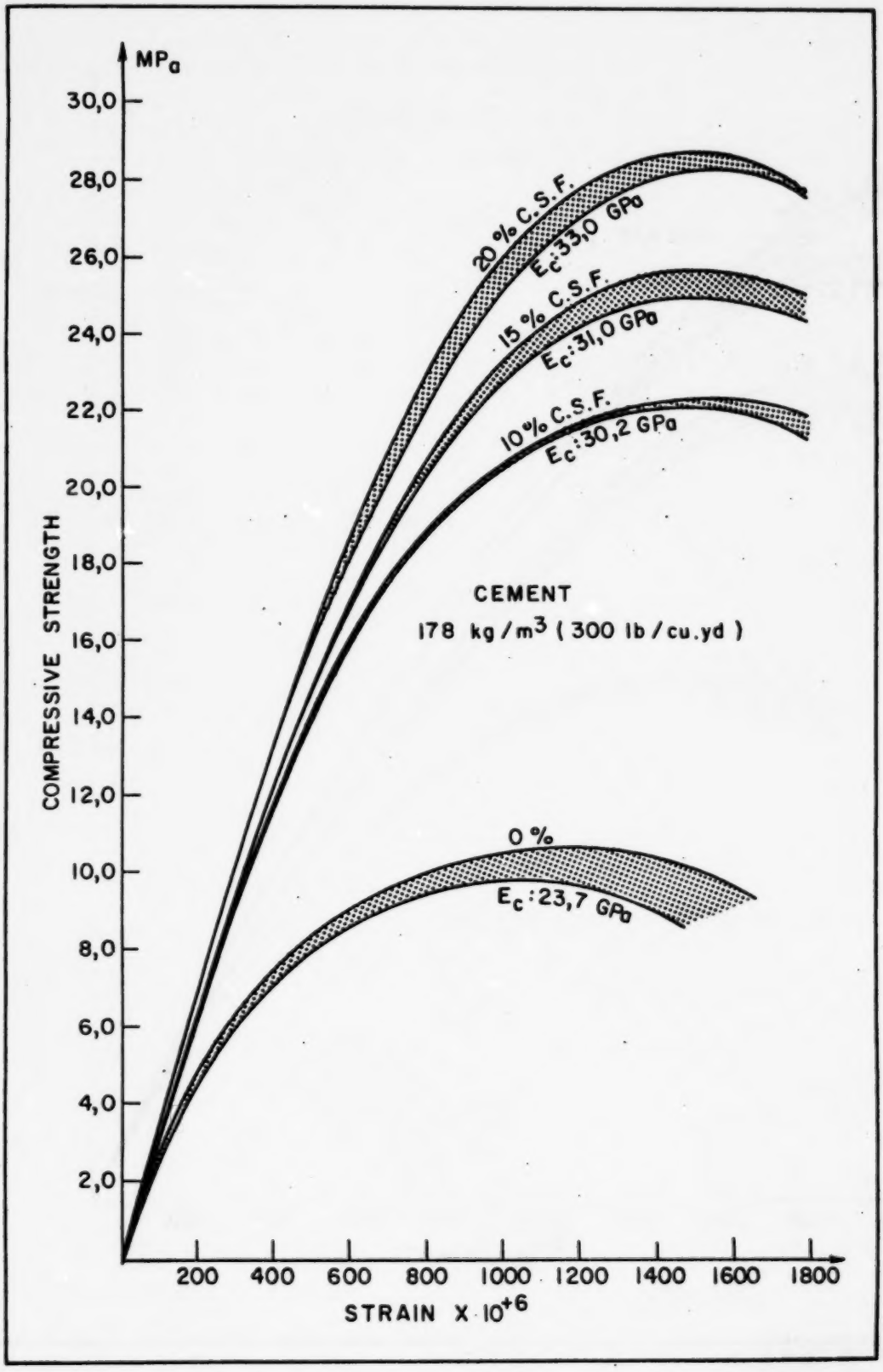

MPa
30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
6,0
4,0
2,0
COMPRESSIVE STRENGTH
20 % C.S.F.
Ec:33,0 GPa
15 % C.S.F.
Ec:31,0 GPa
10 % C.S.F.
Ec:30,2 GPa
CEMENT
178 kg/m3 (300 lb/cu.yd)
0 %
Ec:23,7 GPa
200
400
600
800
1000
1200
1400
1600
1800
STRAIN X 10+6

Figure 13

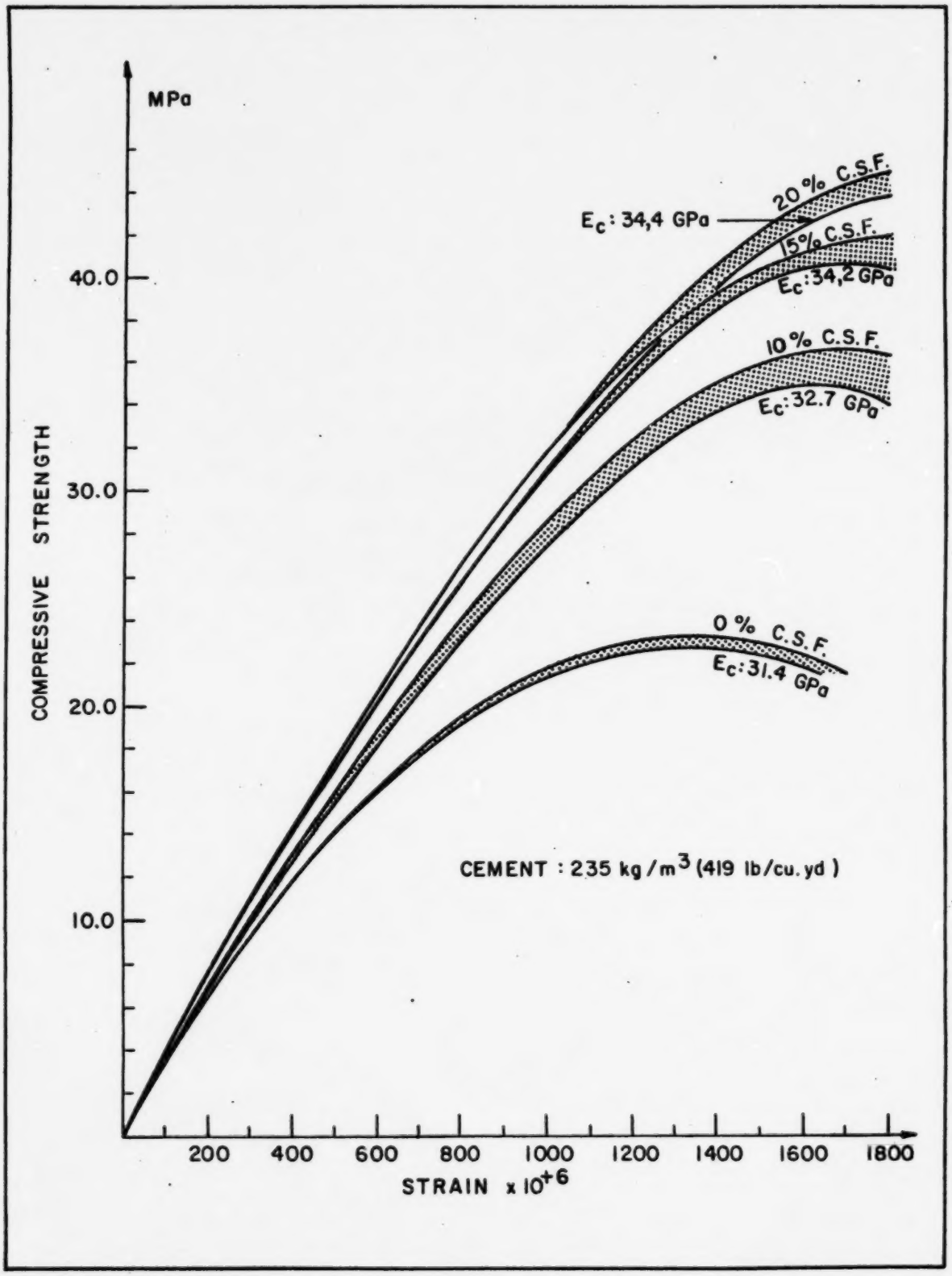

MPa
COMPRESSIVE STRENGTH
40.0
30.0
20.0
10.0
20 % C.S.F.
E_c : 34,4 GPa
15% C.S.F.
E_c : 34,2 GPa
10 % C.S.F.
E_c : 32.7 GPa
0 % C.S.F.
E_c : 31.4 GPa
CEMENT : 235 kg / m^3 (419 lb/cu. yd)
200
400
600
800
1000
1200
1400
1600
1800
STRAIN x 10^{+6}

Figure 14

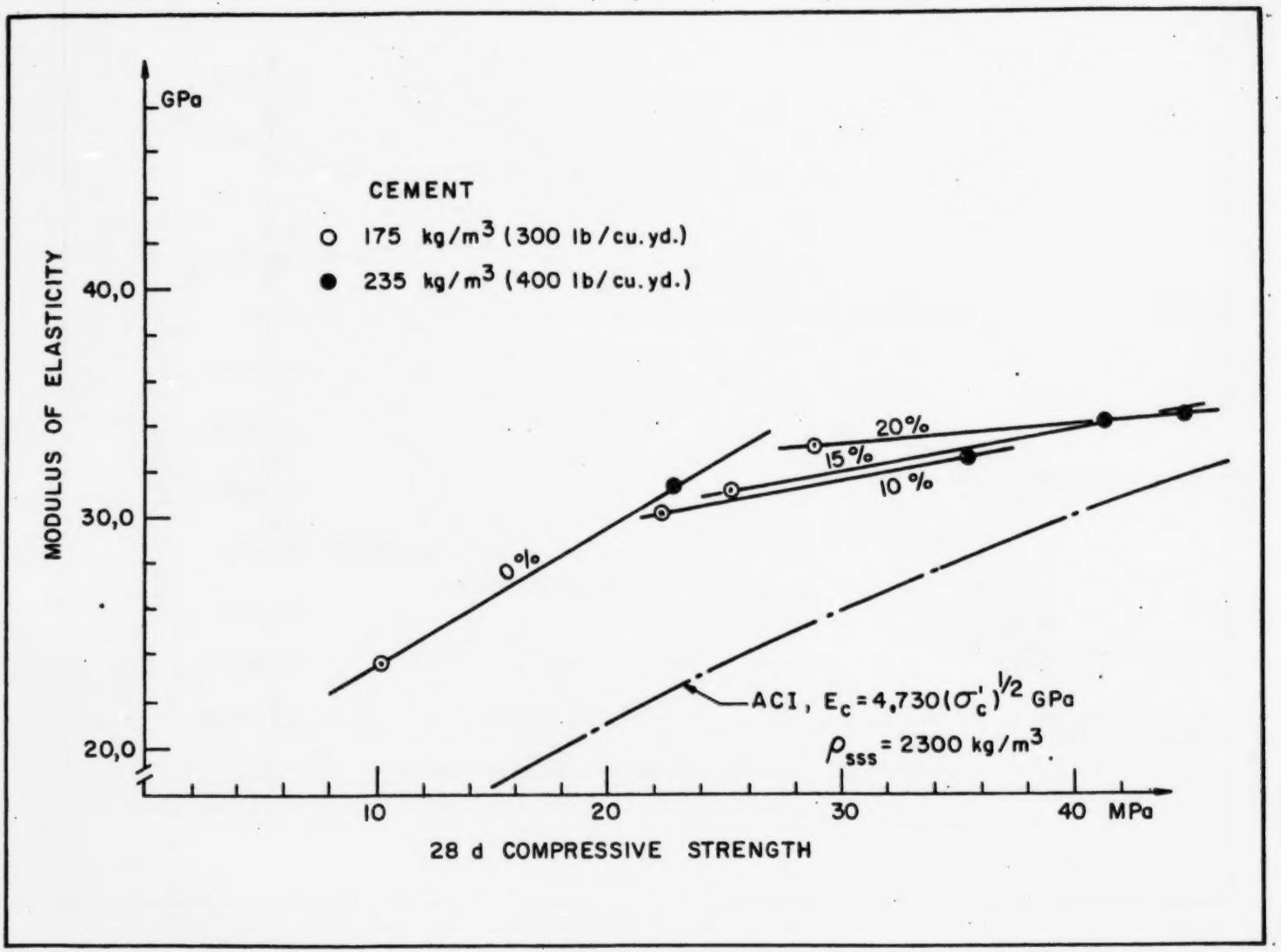

GPa
CEMENT
○ 175 kg/m3 (300 lb/cu.yd.)
● 235 kg/m3 (400 lb/cu.yd.)
MODULUS OF ELASTICITY
40,0
30,0
20,0
20%
15%
10%
0%
ACI, Ec = 4,730(σ'c)1/2 GPa
ρsss = 2300 kg/m3
10
20
30
40 MPa
28 d COMPRESSIVE STRENGTH

Figure 15

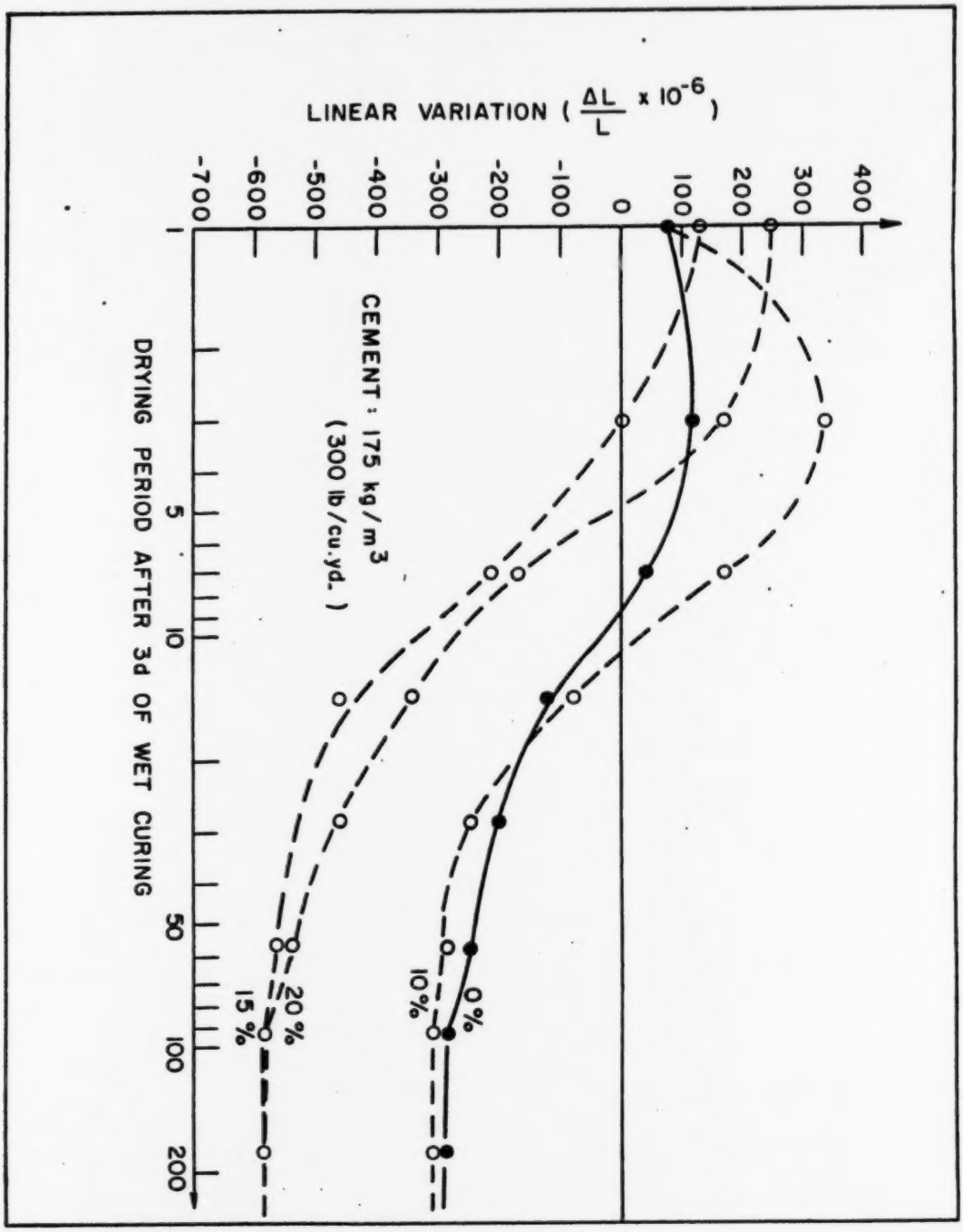

LINEAR VARIATION ($\frac{\Delta L}{L} \times 10^{-6}$)
-700
-600
-500
-400
-300
-200
-100
0
100
200
300
400
CEMENT : 175 kg/m³
(300 lb/cu.yd.)
DRYING PERIOD AFTER 3d OF WET CURING
1
5
10
50
100
200
20 %
15 %
10%
0%

Figure 16

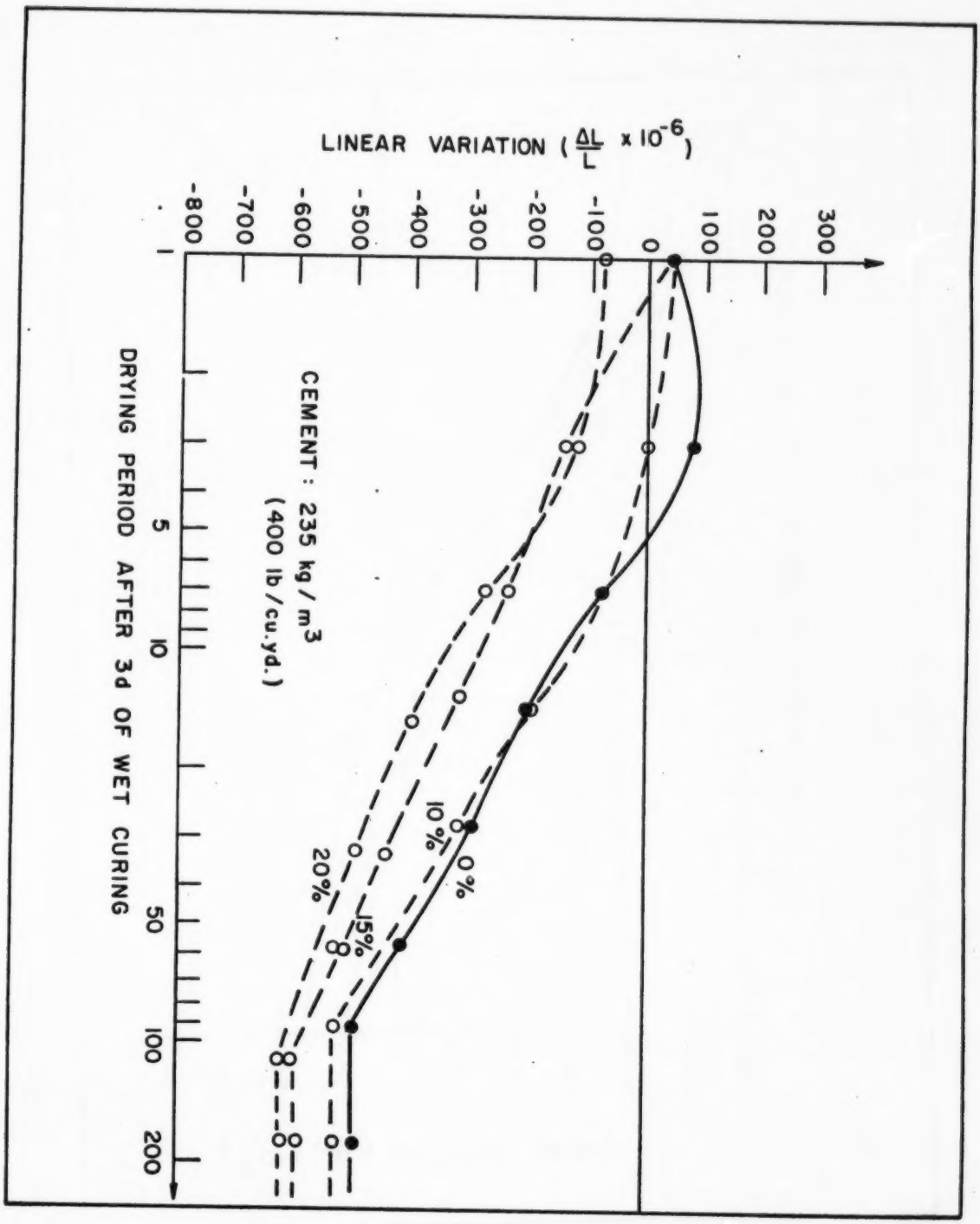

LINEAR VARIATION ($\frac{\Delta L}{L} \times 10^{-6}$)
-800
-700
-600
-500
-400
-300
-200
-100
0
100
200
300
1
5
10
50
100
200
DRYING PERIOD AFTER 3d OF WET CURING
CEMENT : 235 kg / m3
(400 lb / cu.yd.)
20%
15%
10%
0%

Figure 17

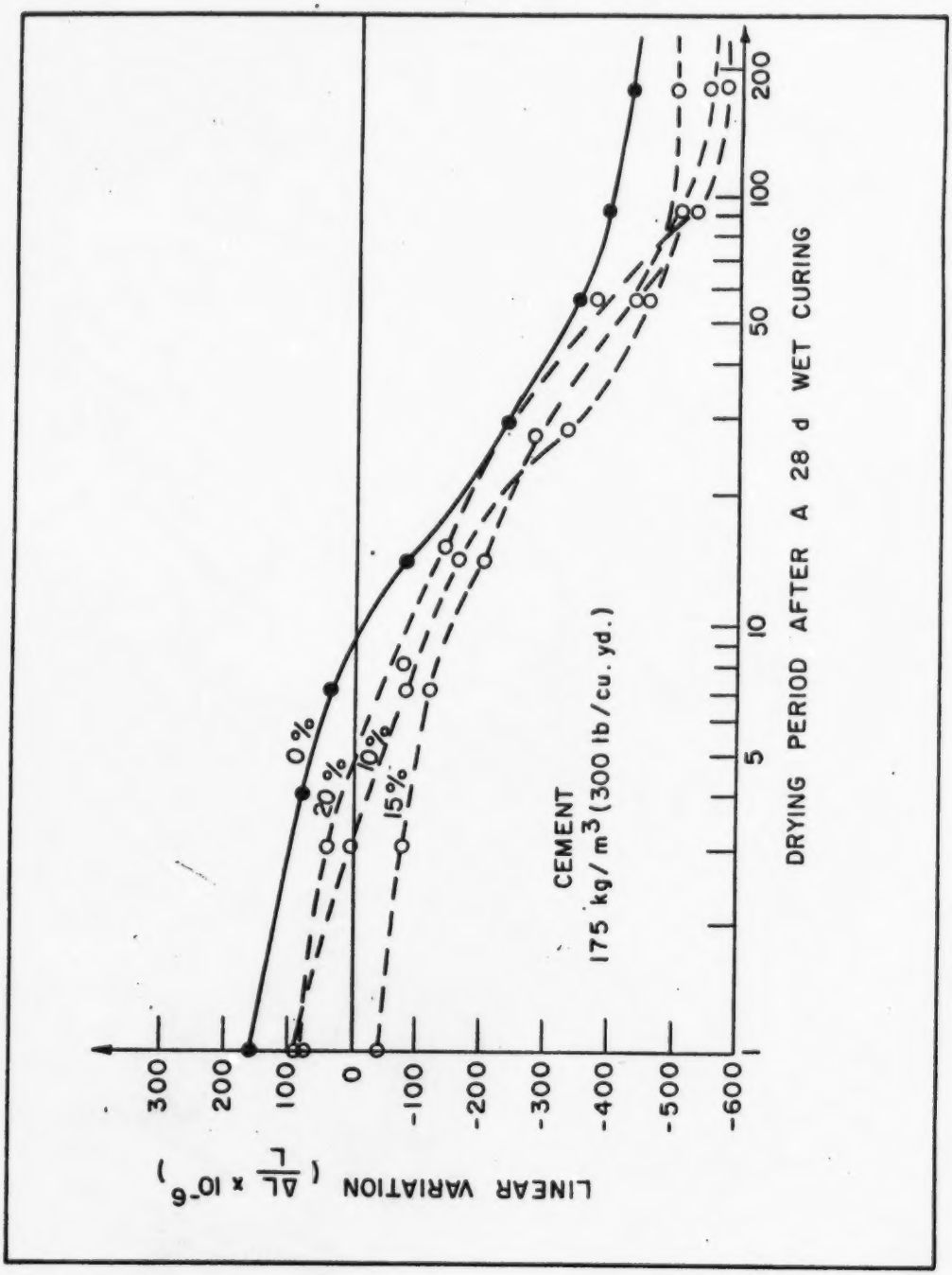

LINEAR VARIATION ($\frac{\Delta L}{L} \times 10^{-6}$)
300
200
100
0
-100
-200
-300
-400
-500
-600
1
5
10
50
100
200
DRYING PERIOD AFTER A 28 d WET CURING
CEMENT
175 kg/m³ (300 lb/cu. yd.)
0 %
20 %
10%
15%

Figure 18

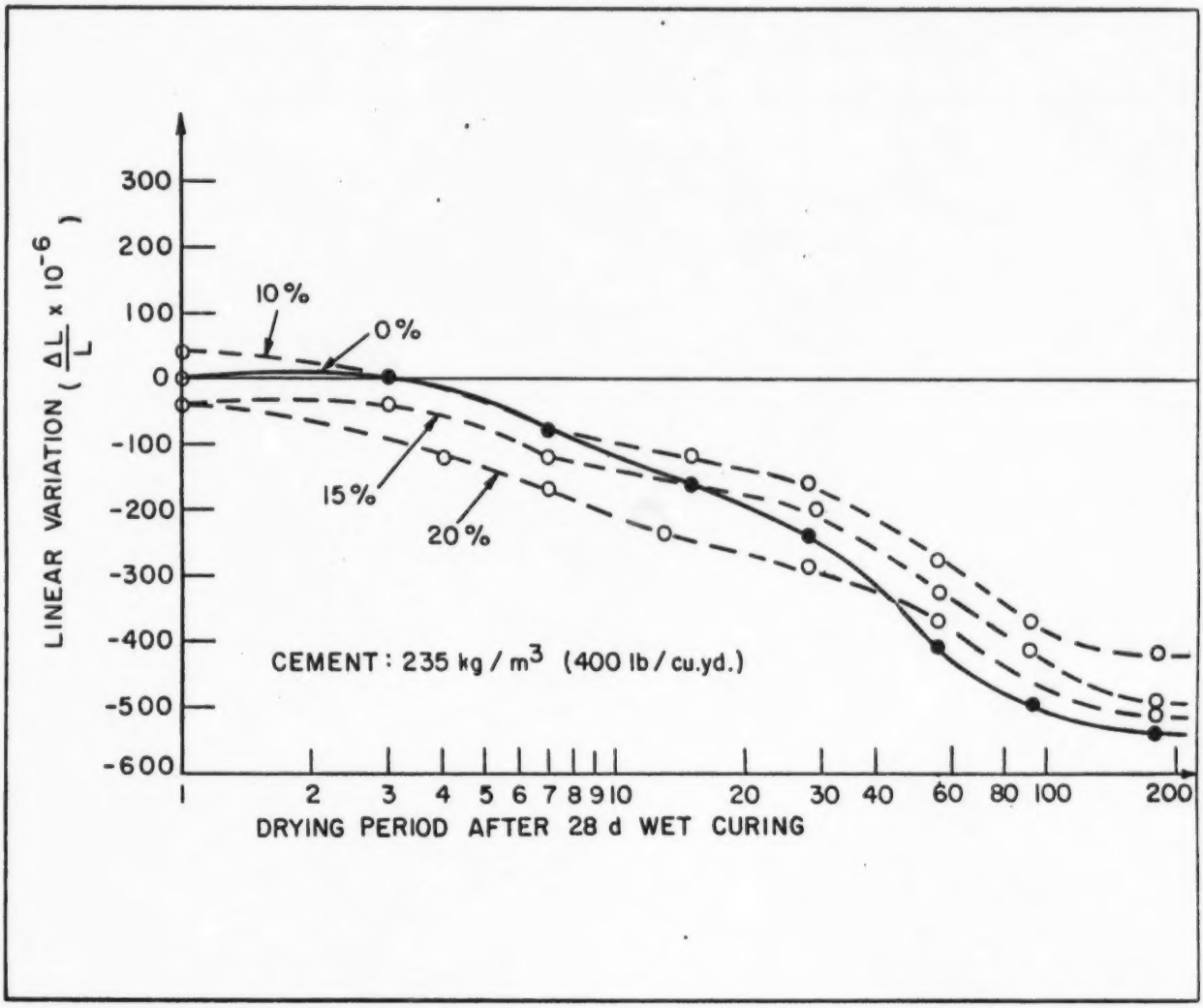

LINEAR VARIATION (ΔL/L x 10^-6)
300
200
100
0
-100
-200
-300
-400
-500
-600
10%
0%
15%
20%
CEMENT : 235 kg / m3 (400 lb / cu.yd.)
1
2
3
4
5
6
7
8
9
10
20
30
40
60
80
100
200
DRYING PERIOD AFTER 28 d WET CURING

Figure 19

APPENDIX

CARACTERISTIQUES DES BETONS FRAIS

PROGRAMME A		0 %				10 %				15 %				20 %			
description \ mélanges		AA 1	AA 2	AA 3	AA 4	AB 5	AB 6	AB 7	AB 8	AC 9	AC 10	AC 11	AC 12	AD 13	AD 14	AD 15	AD 16
composition (Kg/m³)	eau	177	174	175	173	175	178	173	175	178	178	173	174	175	179	174	172
	ciment	177	174	177	174	175	178	172	175	178	177	173	173	175	178	174	174
	pierre	995	978	994	978	983	1003	968	983	1006	1001	980	984	982	1004	978	983
	sable	936	919	934	920	925	943	910	925	936	932	953	958	923	943	919	916
%	Si O_2	0	0	0	0	10	10	10	10	15	15	15	15	20	20	20	20
caractéristiques	aff (mm)	75	85	75	75	75	70	110	75	80	75	75	75	70	75	80	75
	air %	6,4	6,4	6,3	6,3	6,2	5,3	7,4	6,1	5,8	5,0	5,8	6,4	6,4	4,6	6,5	6,5
	mas Vol (Kg/m³)	2285	2245	2280	2245	2275	2320	2240	2275	2325	2315	2305	2315	2290	2340	2280	2280
	E/ (c+Si O_2)	1,00	1,00	0,99	0,99	0,91	0,91	0,92	0,91	0,87	0,87	0,87	0,87	0,83	0,84	0,83	0,82
adjuvants	Darex cm³/Kg	0,38	0,38	0,38	0,38	0,54	0,54	0,54	0,54	0,65	0,59	0,65	0,65	0,82	0,72	0,83	0,76
	Mighty (L/m³)	—	—	—	—	1,85	1,18	—	0,98	0,98	1,5	0,85	0,56	0,86	1,51	0,83	0,47

PROGRAMME B																	
description \ mélanges		BA 1	BA 2	BA 3	BA 4	BB 5	BB 6	BB 7	BB 8	BC 9	BC 10	BC 11	BC 12	BD 13	BD 14	BD 15	BD 16
Composition (Kg/m³)	eau	162	160	162	159	162	160	165	165	159	159	159	159	160	159	161	160
	ciment	239	236	239	233	239	237	237	237	235	235	235	235	236	234	237	236
	pierre	1049	1040	1049	1029	1052	1040	1043	1043	1033	1036	1033	1036	1037	1030	1044	1037
	sable	870	864	870	884	873	864	866	866	858	860	858	860	860	855	866	860
%	Si O_2	0	0	0	0	10	10	10	10	15	15	15	15	20	20	20	20
caractéristiques	aff (mm)	75	75	75	70	75	80	75	75	85	75	85	75	75	80	80	75
	air (%)	6,4	6,4	6,3	6,6	5,8	6,4	5,4	6,0	6,0	5,7	6,1	5,9	5,8	6,0	5,4	5,8
	mas Vol (Kg/m³)	2320	2300	2320	2305	2350	2325	2330	2330	2320	2325	2320	2325	2340	2325	2355	2340
	E/(c+Si O_2)	0,68	0,68	0,68	0,68	0,62	0,61	0,63	0,63	0,59	0,59	0,59	0,59	0,57	0,57	0,57	0,57
adjuvants	Darex (cm³/kg)	0,27	0,29	0,26	0,27	0,52	0,52	0,52	0,52	0,64	0,64	0,64	0,64	0,79	0,79	0,79	0,82
	Mighty (L/m³)	—	—	—	—	0,94	1,22	1,59	1,22	1,91	1,89	1,82	1,82	2,11	2,12	2,45	2,43

	A-0	A-10	A-15	A-20
1 d	2,6	2,4	2,5	3,0
7 d	7,9	11,3	12,5	13,3
28 d	11,4	22,6	24,7	26,7
91 d	13,5	26,5	29,6	31,2
365 d	12,8	27,1	30,5	33,7

	B-0	B-10	B-15	B-20
1 d	4,9	7,7	10,4	9,0
7 d	16,3	25,5	28,3	30,3
28 d	22,0	39,6	42,4	45,1
91 d	25,7	44,2	47,3	50,1
365 d	25,9	45,8	50,2	50,9

Compressive strength of the A and B programs in MPa

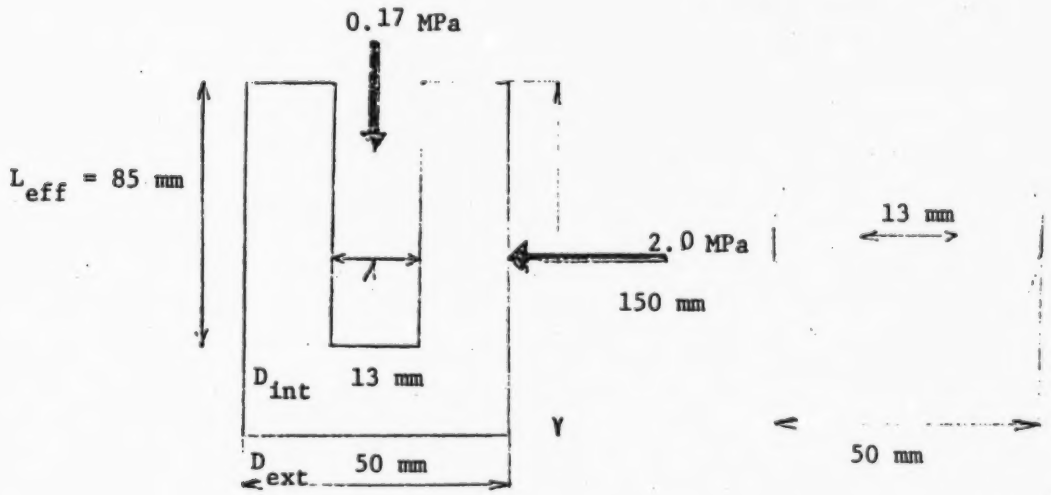
PART II

Permeability of Condensed Silica Fume Concretes

PERMEABILITY MEASUREMENTS

The permeability of the concretes of program A and B has been measured with a BERNAIX type permeameter built at the University of Sherbrooke.

The permeability of five samples has been simultaneously measured, see Figure 1. The samples had the following geometrical characteristics.



The flow was convergent with a head of 2.0 MPa (300 psi) and a back pressure of 0.17 MPa (25 psi) was applied. The permeability of the concrete is given by the following formula:

$$k = \frac{Q \cdot \ell n \frac{D_{ext}}{D_{int}}}{2\pi \cdot L_{eff} \cdot \Delta P}$$

Q is the water flow

D_{ext} is the outside diameter of the concrete sample

D_{int} is the diameter of the inside hole

L_{eff} is the effective length of the inside hole

ΔP is the effective water head (exterior water head minus interior back pressure).

At the beginning of the test the samples were saturated under vacuum with distilled and deaerated water.

In Figures 2 to 5 the volume of water that has been flowing through the samples A-0, A-10, B-0 and B-10 has been plotted as a function of the time. The slope of these curves give the permeability coefficient.

Discussion of the results

The values of the permeability coefficient are presented in Table 1. It can be seen from this table that:

1°) the permeability of the concrete is decreasing as the cement dosage is increasing (comparison of A-0 and B-0 concrete),

2°) the introduction of condensed silica fume in the concrete drastically decreases the permeability of the concrete (comparison of A-0 and A-10 and of B-0 and B-10), see Figure 6.

3°) the permeability of concrete A-10 is about the same as concrete B-0. These 2 concretes had already the same compressive strength, the same elastic modulus and the same pore size distribution below 0.1 μm.

	Program A		Program B	
	A-0 %	A-10 %	B-0 %	B-10 %
K in m/s	6.7×10^{-11}	1.1×10^{-13}	4.3×10^{-13}	1.3×10^{-14}
	1.4×10^{-11}	1.8×10^{-13}	6.5×10^{-13}	1.7×10^{-14}
	1.4×10^{-11}	4.0×10^{-13}	8.5×10^{-13}	2.0×10^{-14}
	2.2×10^{-10}	5.2×10^{-13}	20×10^{-13} *	**
	2.7×10^{-10}	5.9×10^{-13}	-	**
Average	1.2×10^{-10}	3.6×10^{-13}	5.4×10^{-13}	1.7×10^{-14}

* This sample has been probably damaged when introduced in the cell.

** The water flow was unmeasurable with our apparatus. The two samples can be considered impervious.

Table 1 - Permeability coefficient

4°) the concrete B-10 has a permeability at the limit of our apparatus.

Comments on the measurements

As can be seen from Figures 2 to 5 there is a big difference in the shape of the curves water flow vs time for the concretes containing or not condensed silica fume. For a plain concrete there is a constant increase of the water flow with time and it is impossible to reach a stable water flow. (In fact we have observed a washing of the lime of the concrete).

But for the concrete containing condensed silica fume the water flow is decreasing with the time. In this case a constant flow is reached more or less rapidly. When the concrete is containing condensed silica fume all the lime has been fixed and cannot be washed.

Conclusion of the permeability measurements

The use of condensed silica fume in concrete decreases drastically the permeability. As all the lime liberated during the hydration of the cement has been fixed in the form of secondary C-S-H the water flow through the concrete containing condensed silica fume is decreased drastically. In the contrary in a normal concrete the washing of the lime increases the permeability of the concrete with the time.

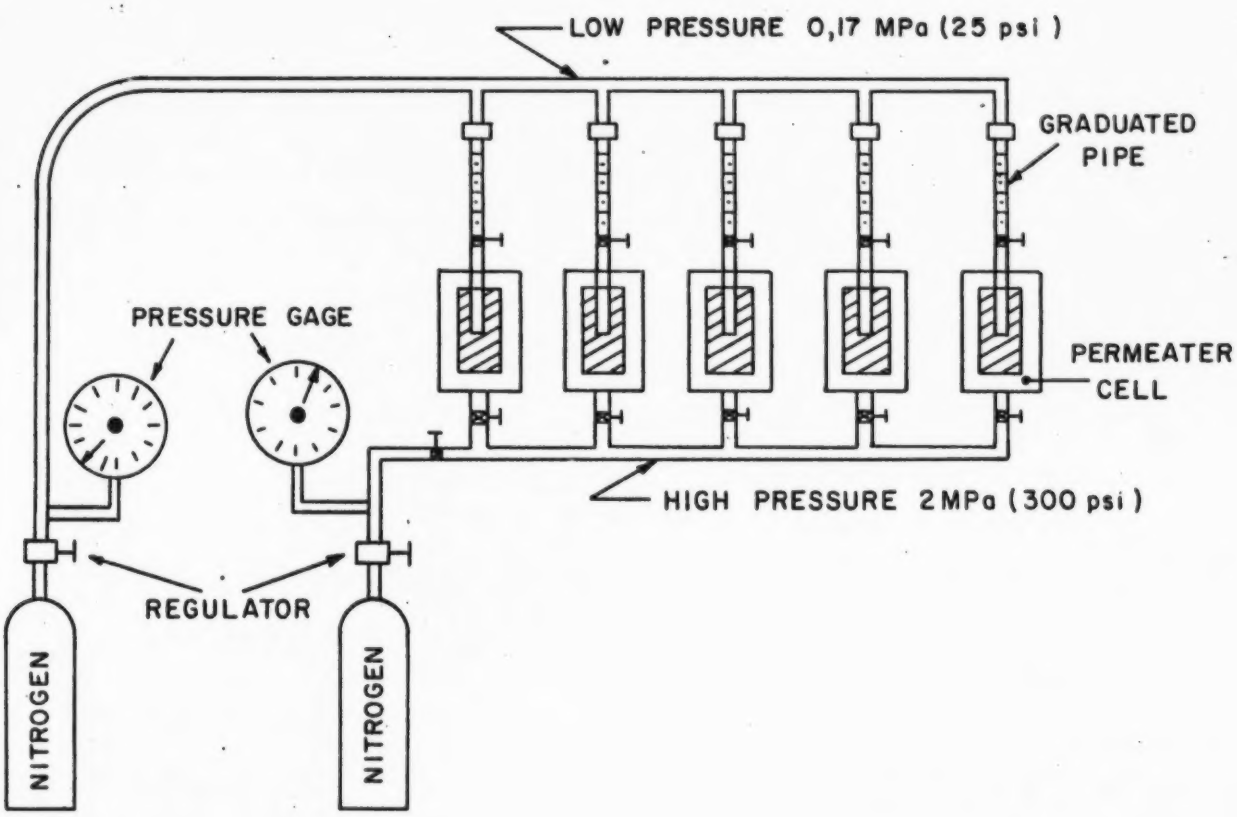


Figure 1- Principle of the BERNAIX permeameter.

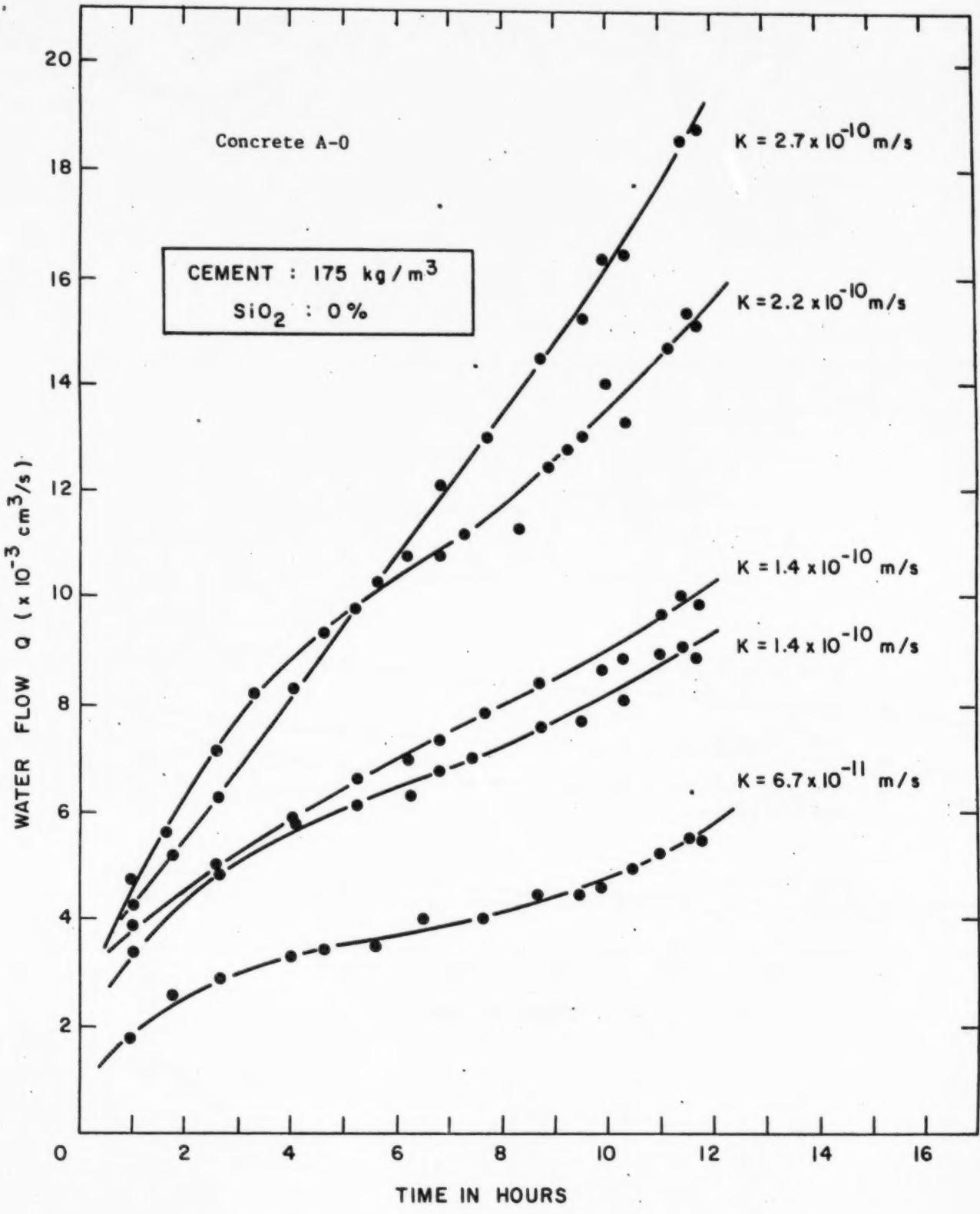


Figure 2- Water flow for A-0 concrete.

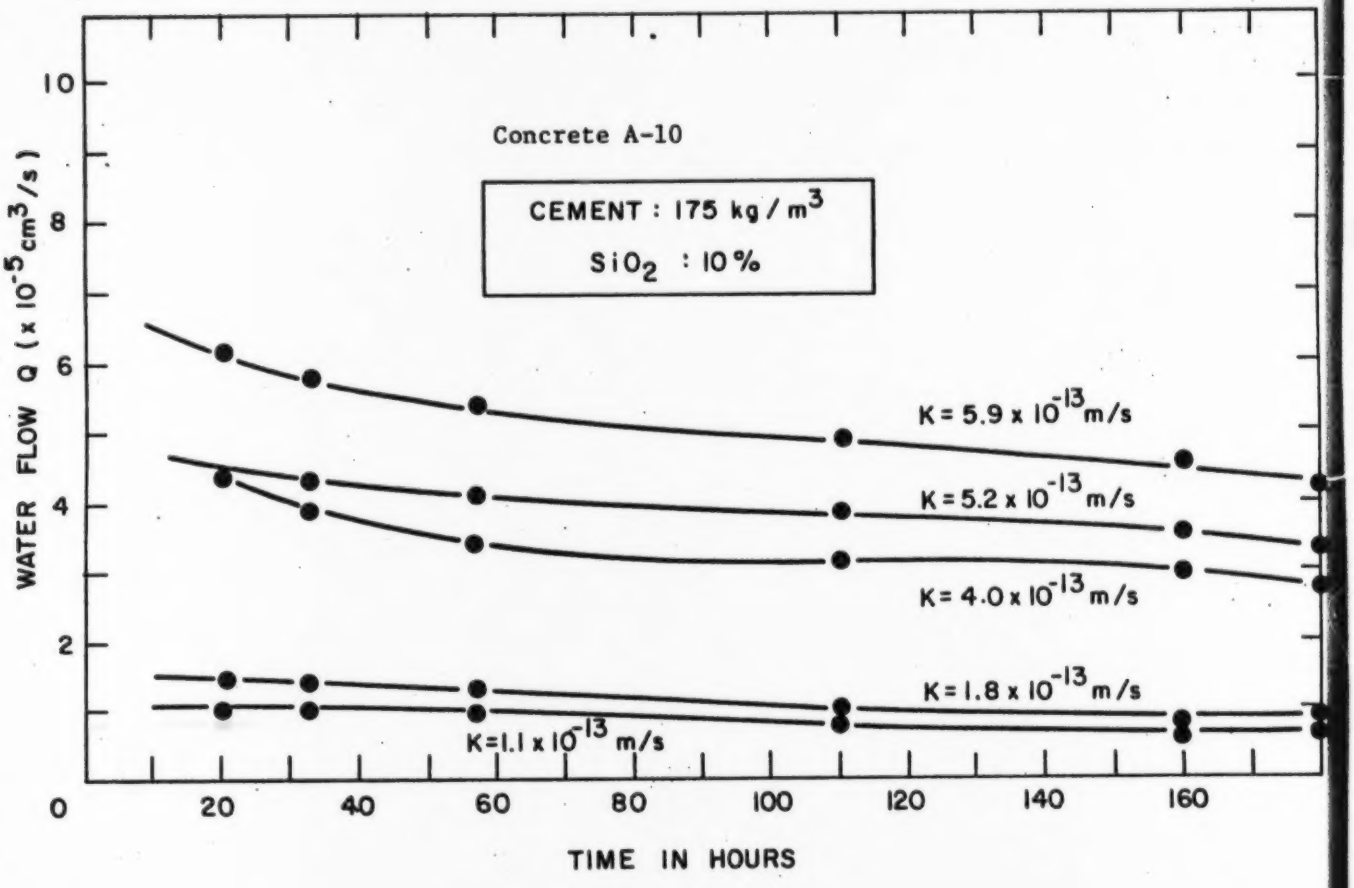


Figure 3- Water flow for A-10 concrete

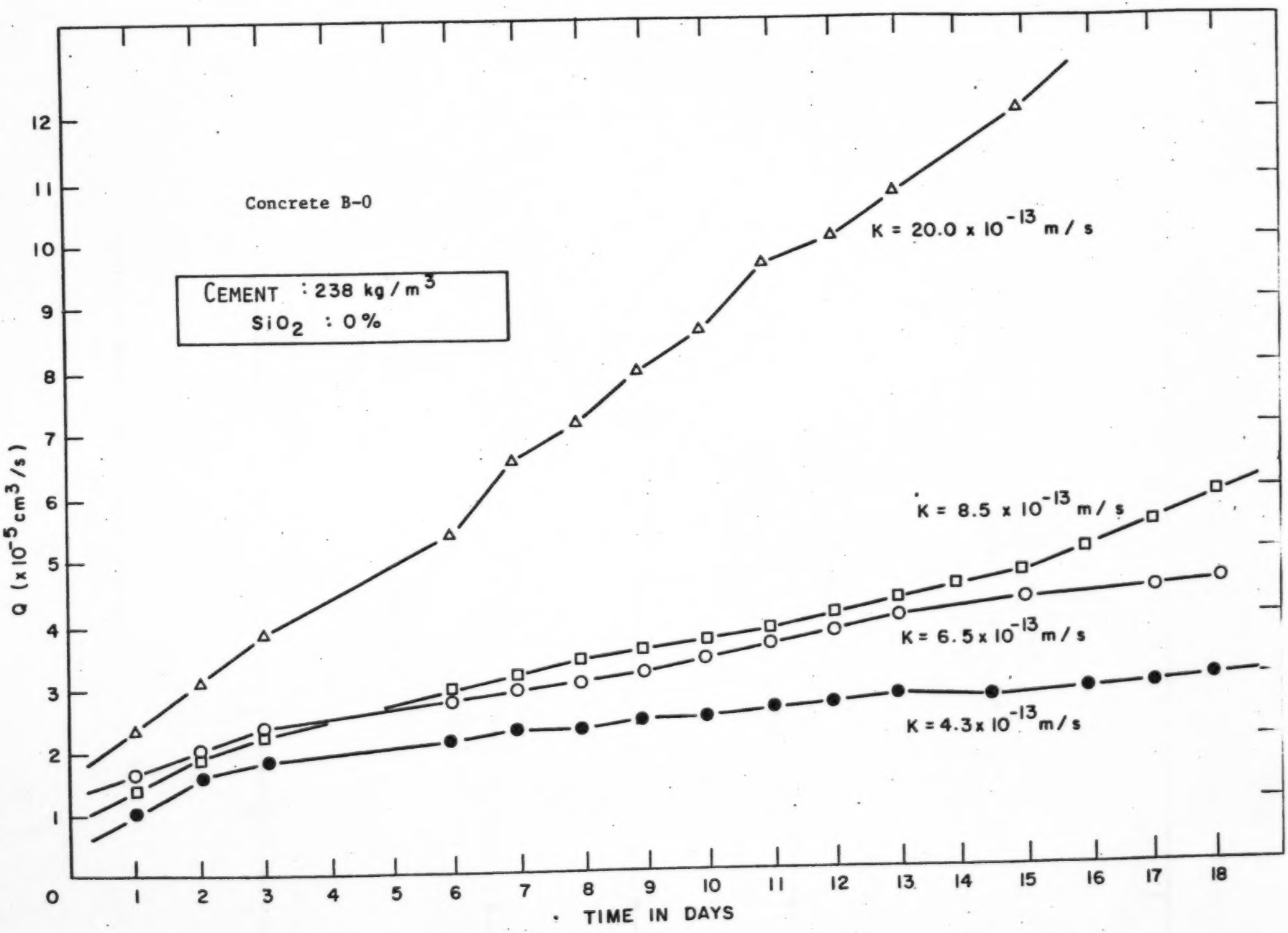


Figure 4- Water flow for B-0 concrete

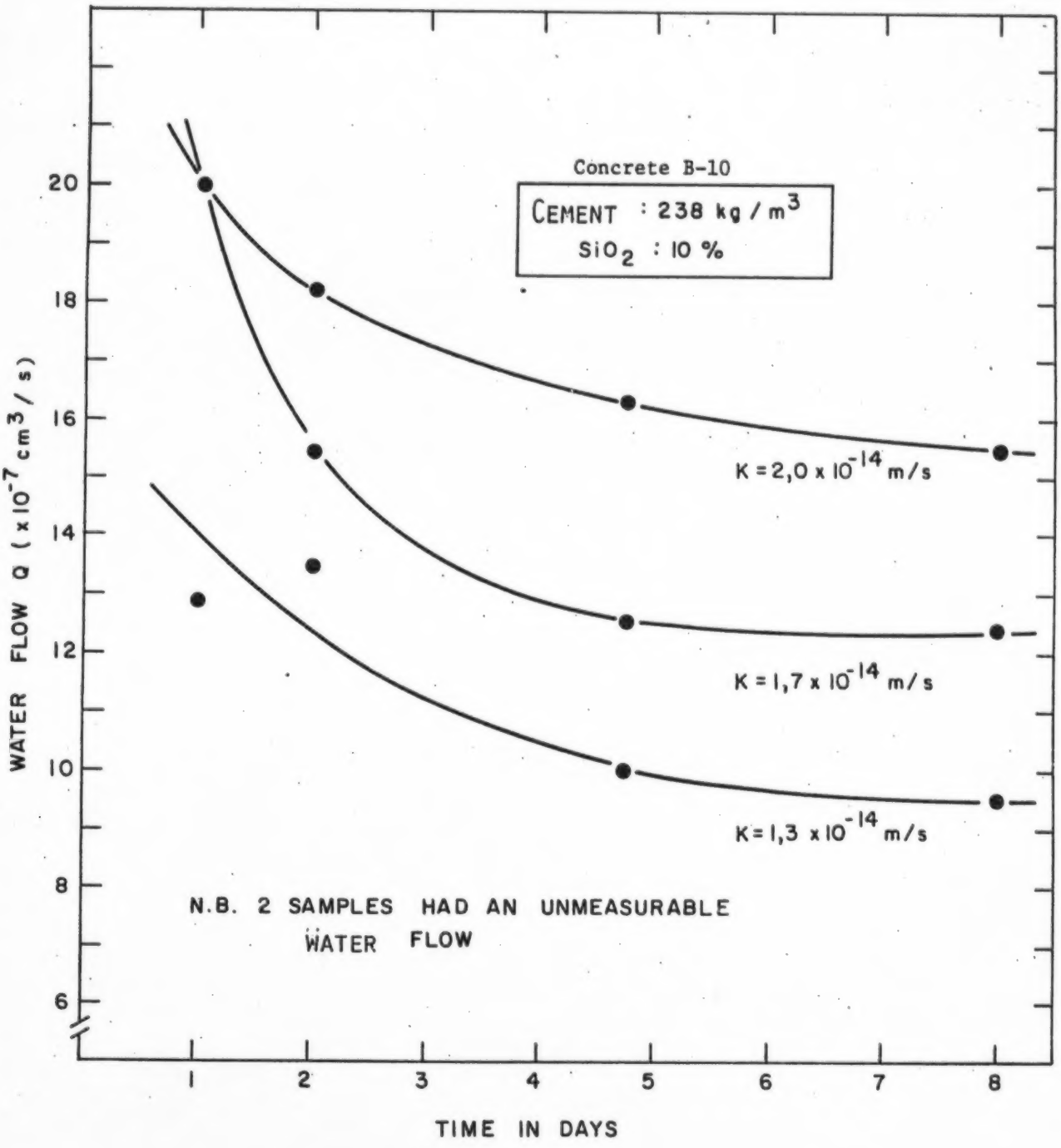


Figure 5- Water flow for B-10 concrete

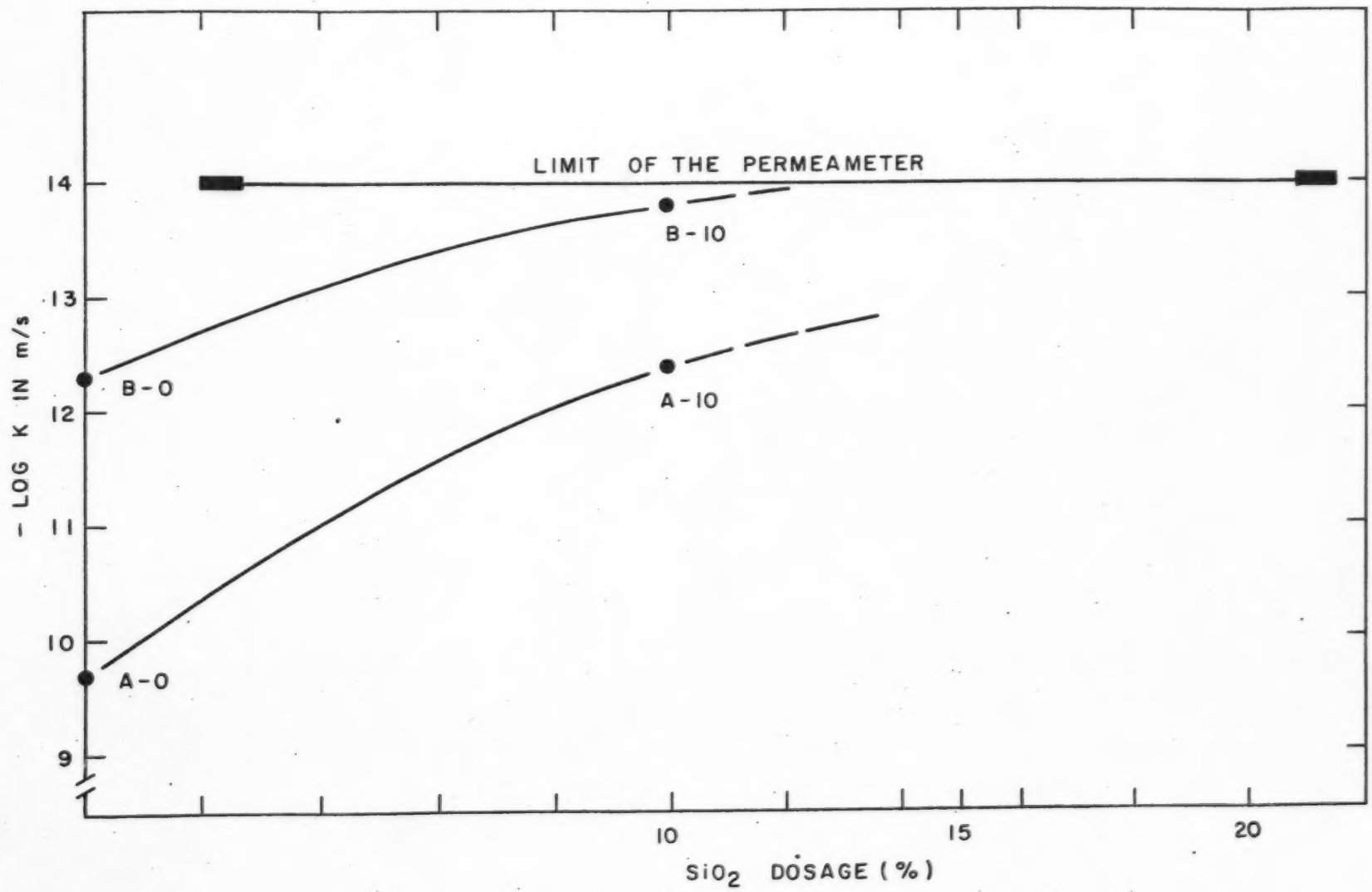


Figure 6- Permeability of the various concrete as a function of the silica dosage

PART III

Porosity of Condensed Silica Fume Concretes

PORE SIZE DISTRIBUTION

Note: These measurements have been done by Pierre Delage a post doc working at the civil engineering department.

A pore size analysis has been made on a sample of the 8 different concretes with a Carlo Erba porosimeter. This porosimeter permitts to measure pore diameters down to 50A, that corresponds to an applied pressure of 150 MPa on the mercury. The measurement cell of this porosimeter is one of the largest available for such a range of pressure, permitting to work with samples having the following maximum size ;ϕ = 16 mm (5/8"), h = 50 mm (2"), and weighing approximately 20 to 25 g. Manmohan and Mehta who have published some results on the porosity of cement paste have done their measurements on samples weighing only 4 g.

Due to the size of our samples it has been possible to make the pore size analysis on a piece of concrete instead of a piece of cement paste. However in order to take into account that some of the samples could contain more or less of non porous aggregate particles (due to the non homogeneous nature of the concrete) all the results have been plotted on a percentage basis. A 100 percent value has been given to the total volume of mercury that was injected in the sample at the end of the experiment. The volume of mercury injected at each pressure level has been compared to this total volume and expressed as a percentage of it.

N.B. This type of representation is similar to the one adopted for the representation of grain size distribution.

As the porosimeter is connected to a computer all the results have been plotted directly in the format that appears in the following Figures 20, 22, 24 and 26.

A first attempt of another type of representation has been made. The derivatives of these cumulative curves has been plotted as a function of the pore size in order to show the histogram of the pore size distribution of the different concrete, Figures 21, 23, 25 and 27, but an additional effort should be made in order to improve this type of representation. Due to lack of funds it has not been possible to write a computer program to adjust the area under these histograms to the same value corresponding to 100 percent. With such a representation it should have been possible to make a comparative study on the intensity of the humps present in the different histograms.

Pore size distribution of the 2 plain concretes A-0 and B-0

(Figures 20 - 21)

It can be seen in Figure 20 that the pore size distribution of the 2 concretes is quite different. The pores of the concrete A are coarser than the pores of concrete B, except in the last part of the curve corresponding to the very fine pores 50 Å to 200 Å where the 2 curves are the same. This last porosity correspond probably to the porosity of the C-S-H and of the aggregates.

If we have a close look at the manner in which these 2 curves reach the X-axis it can be seen that at 50 Å they have a certain slope. That means that there are some pores finer than 50 Å in the concrete.

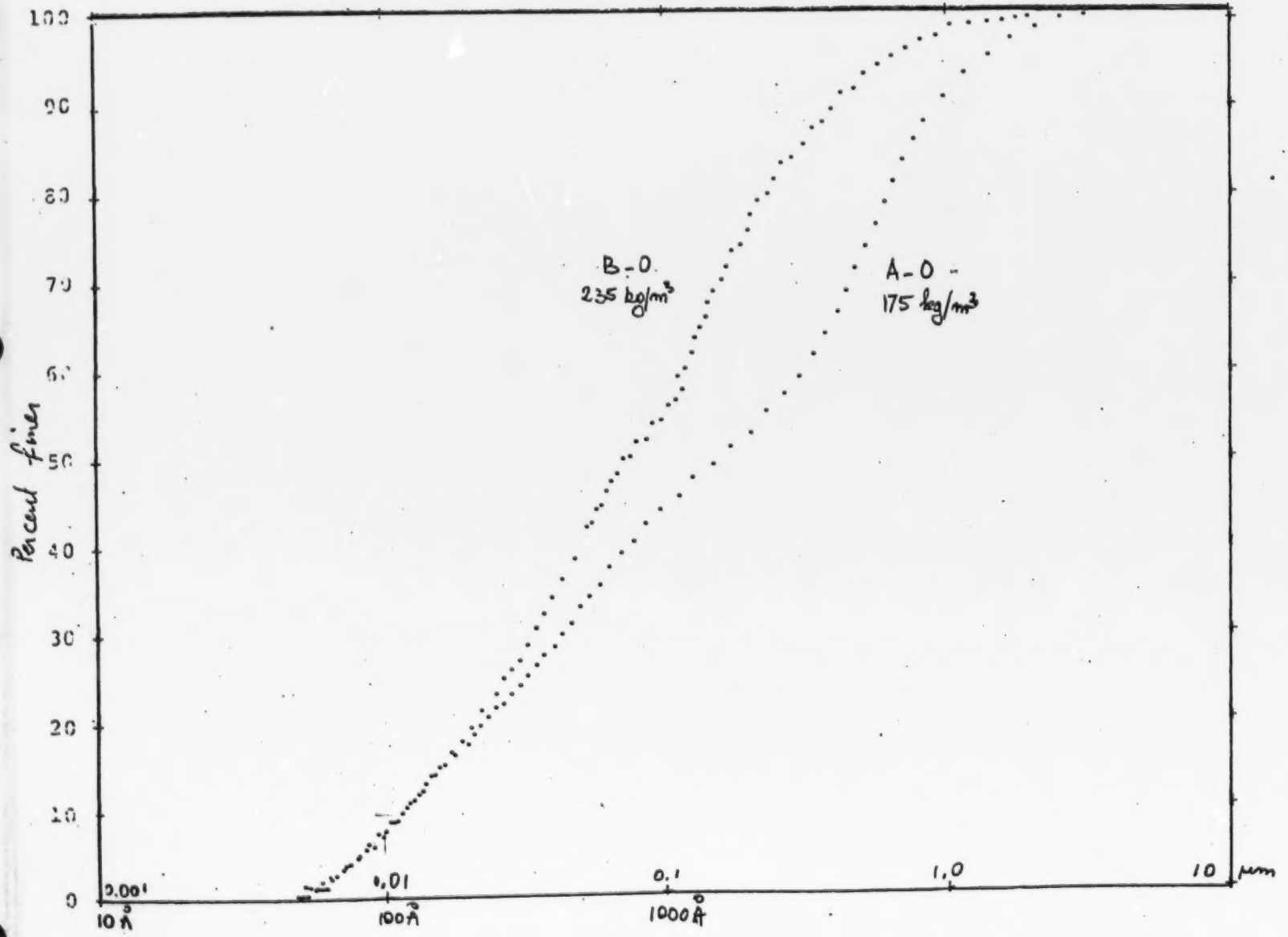


FIGURE 20 COMPARISON OF THE PORE SIZE DISTRIBUTION OF THE REFERENCE CONCRETES A-0 AND B-

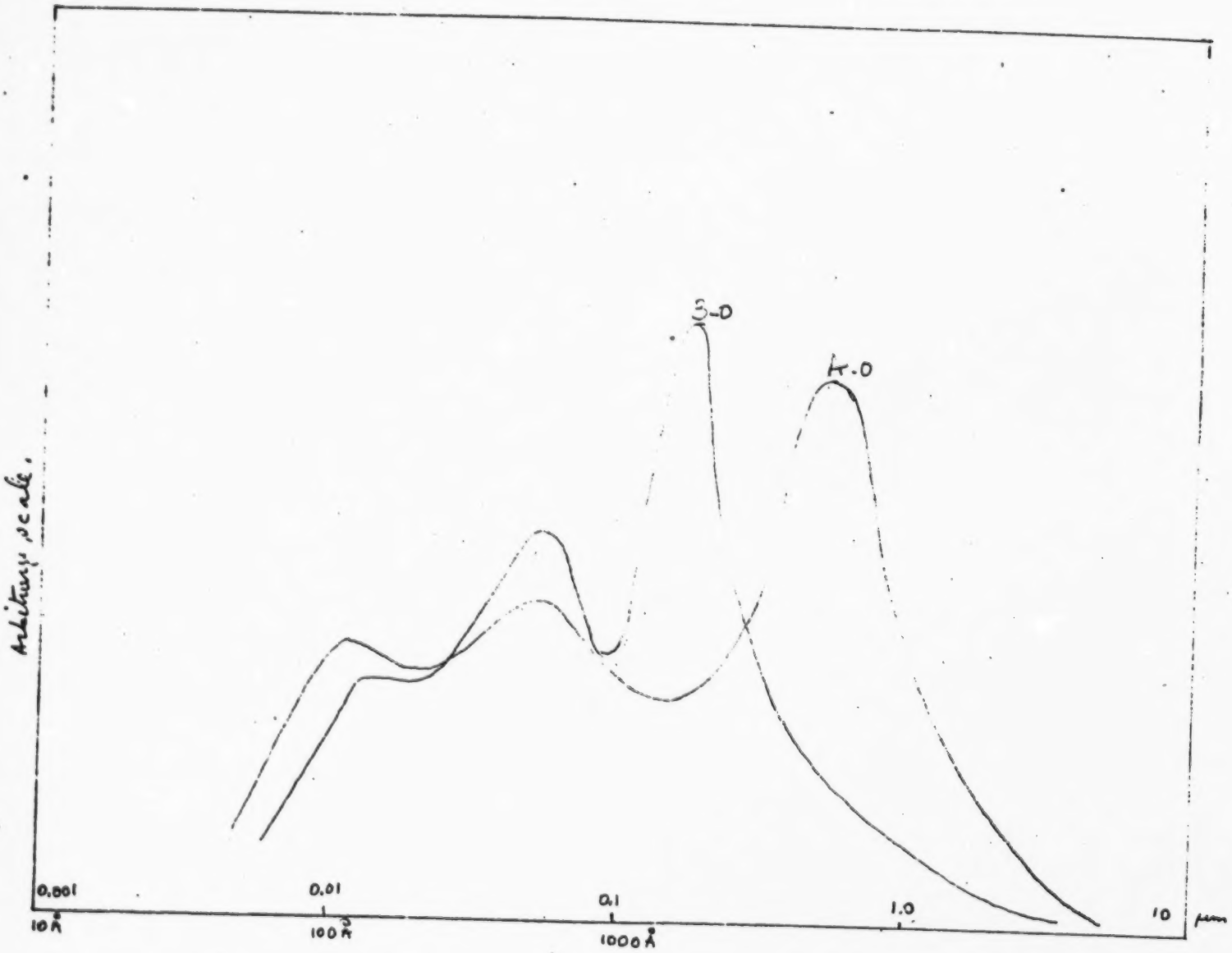


FIGURE 21 COMPARISON OF THE PORE SIZE DISTRIBUTION OF REFERENCE CONCRETES A-0 AND B-(

Figure 21 represents the histogram of the pore size.With this type of representation it can be seen that there exist 3 pore families.

- coarse pores bigger than 1000 Å (0.1 µm)
- medium pores in between 200 and 1000 Å (0.02 to 0.1 µm)
- very fine pores in between 50 and 200 Å (0.005 to 0.02 µm)

The medium and very fine categories are very similar in the 2 concretes as far as the position and the intensity of the two corresponding humps in the histogram are concerned.

But for the coarse pores it can be seen that in concrete A the average size is about 0.6 µm (6000 Å) while in concrete B the average size is only 0.2 µm (2000 Å).

As the water/cement ratio has decreased the average diameter of the coarse pores of the concrete B has drastically decreased as compared to concrete A,making the concrete B stronger and more impervious than concrete A.

Pore size distribution of the concretes of program A- 175 kg/m^3

(Figures 22-23)

The pore size distribution curves of the 4 concretes of program A have been plotted in the same graph. In the case of this very lean mix it can be seen that the addition of C.S.F. is closing a family of pores having between 0.10 and 0.30 µm in diameter (1000 to 3000 Å). The more C.S.F. added the more pronounced is this effect. In the plain concrete a certain lack of pores of this size was already noted but not comparable to what is observed when C.S.F. is added to the mix.

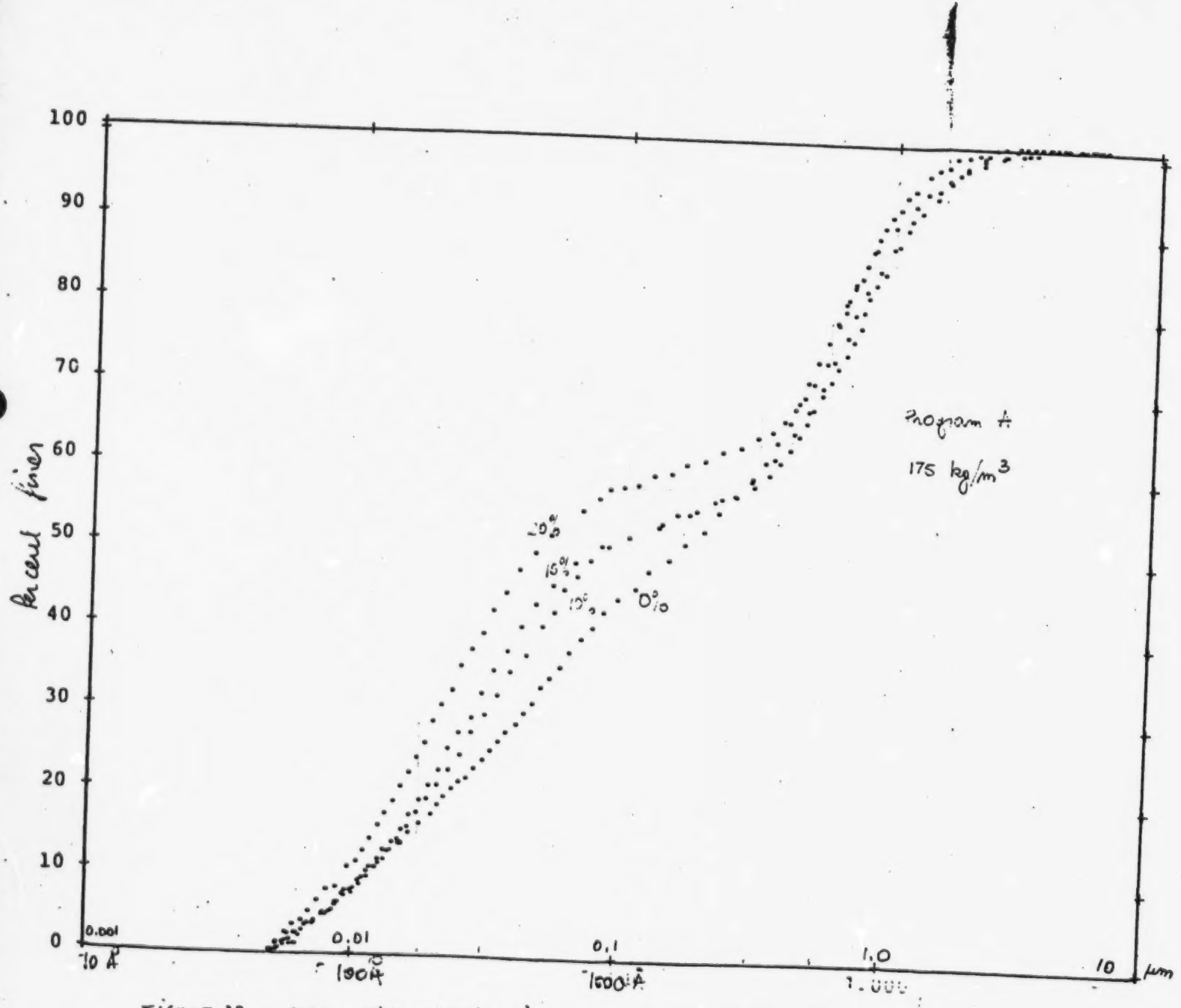


FIGURE 22 - PORE SIZE DISTRIBUTION OF THE CONCRETES OF PROGRAM A

The addition of C.S.F. in this type of mix does not change the pore size distribution of the very fine pores, the curves are the same under 100 Å (except for the 20% addition).

In Figure 23 it can be noted that there is no more a distinction between the medium size pore and the very fine ones, the various histograms for concrete A-10, A-15 and A-20 present only one hump in this area.

Having a close look at the manner in which the curves corresponding to the concretes containing C.S.F. reach the X-axis it can be seen that these curves still present a certain slope at 50 Å indicating that there exist finer pores than 50 Å . The result is in good agreement with the previous observation on the nature of the C-S-H formed when C.S.F. is added to concrete. M. Regourd, A. Buck, D. Roy have shown that this C.S.F. was poorly cristallized but very dense as compared to the C.S.H. of an O.P.C.

Perhaps the third hump in the histogram has been shifted towards smaller size that cannot be reached with our apparatus. It can be noted that the average size of this very fine pores is shifting towards a smaller diameter.

If the pore size curves are compared in their upper part corresponding to coarse pores, it can be seen that the curves are very similar in shape except that a small shift towards a coarser size can be noted in the average diameter of the coarse pores as the percentage of C.S.F. added in the mix is increasing.

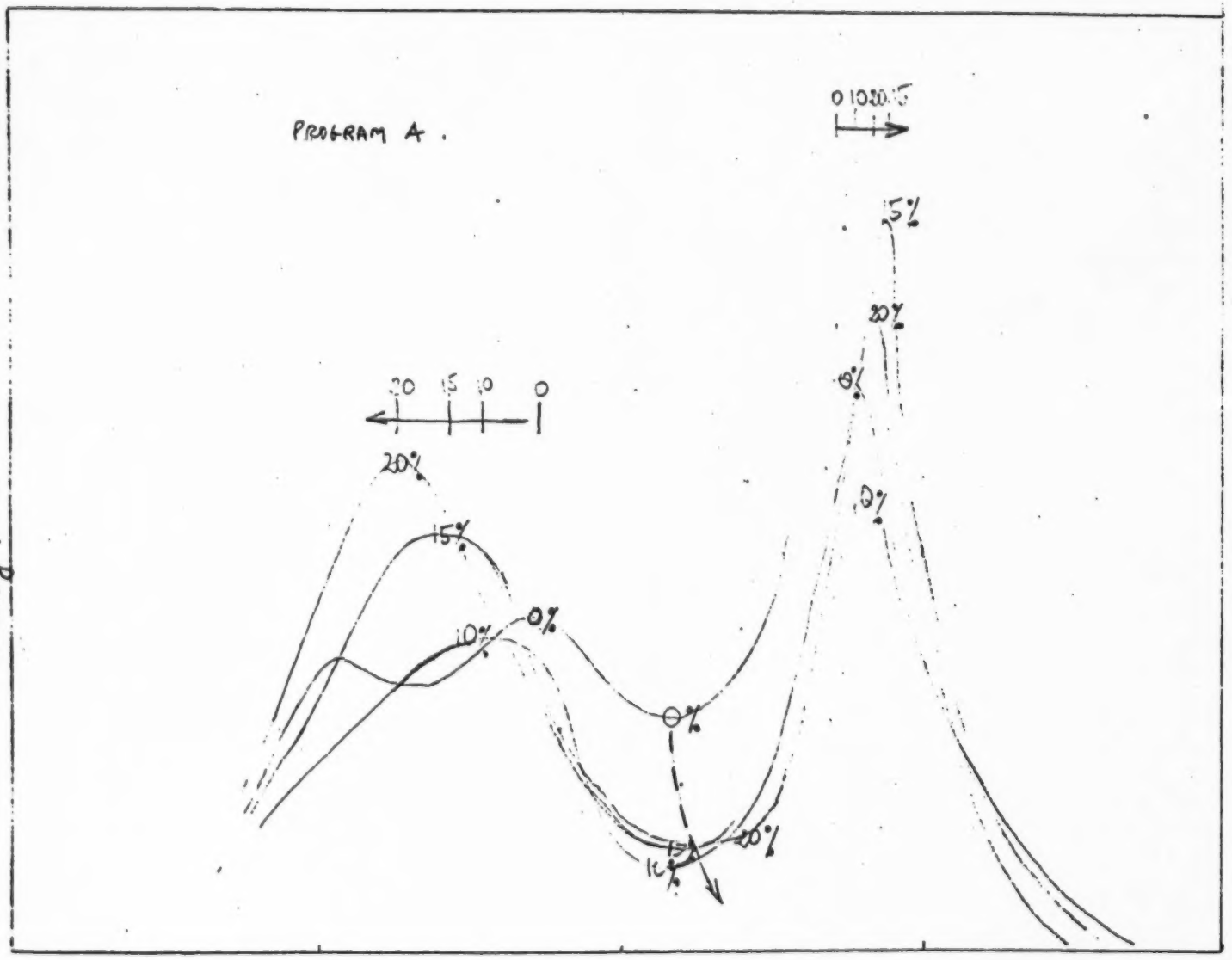


FIGURE 23 - COMPARISON OF THE PORE SIZE DISTRIBUTION OF THE CONCRETES OF PROGRAM A

Pore size distribution of the concretes of program B-235 kg/m^3

(Figures 24-25)

The effect of the C.S.F. addition is about the same as in the previous serie of concrete or even more spectacular. The presence of a gap in the pore size distribution around 0.9 µm is more evident in this richer mix. Again in the concretes containing C.S.F. there are only 2 families of pores (instead of 3 for the plain concretes); medium pores and very coarse with a gap in between that broadens as the C.S.F. content increases. As can be seen in the following Table the average diameter of the finer pores is decreasing as the C.S.F. content in the mix is increasing and the average diameter of the coarser pores is increasing as the C.S.F. content in the mix is increasing as a result of the closure of more and more pores around the 0.1 µm diameter (1000 Å).

average diameter	0	10	15	20
medium pores Å	550	320	230	170
coarse pores µm	0.18	0.25	0.54	0.8
closed pores µm	0.09 very few	0.06 to 0.15	0.05 to 0.30	0.04 to 0.45

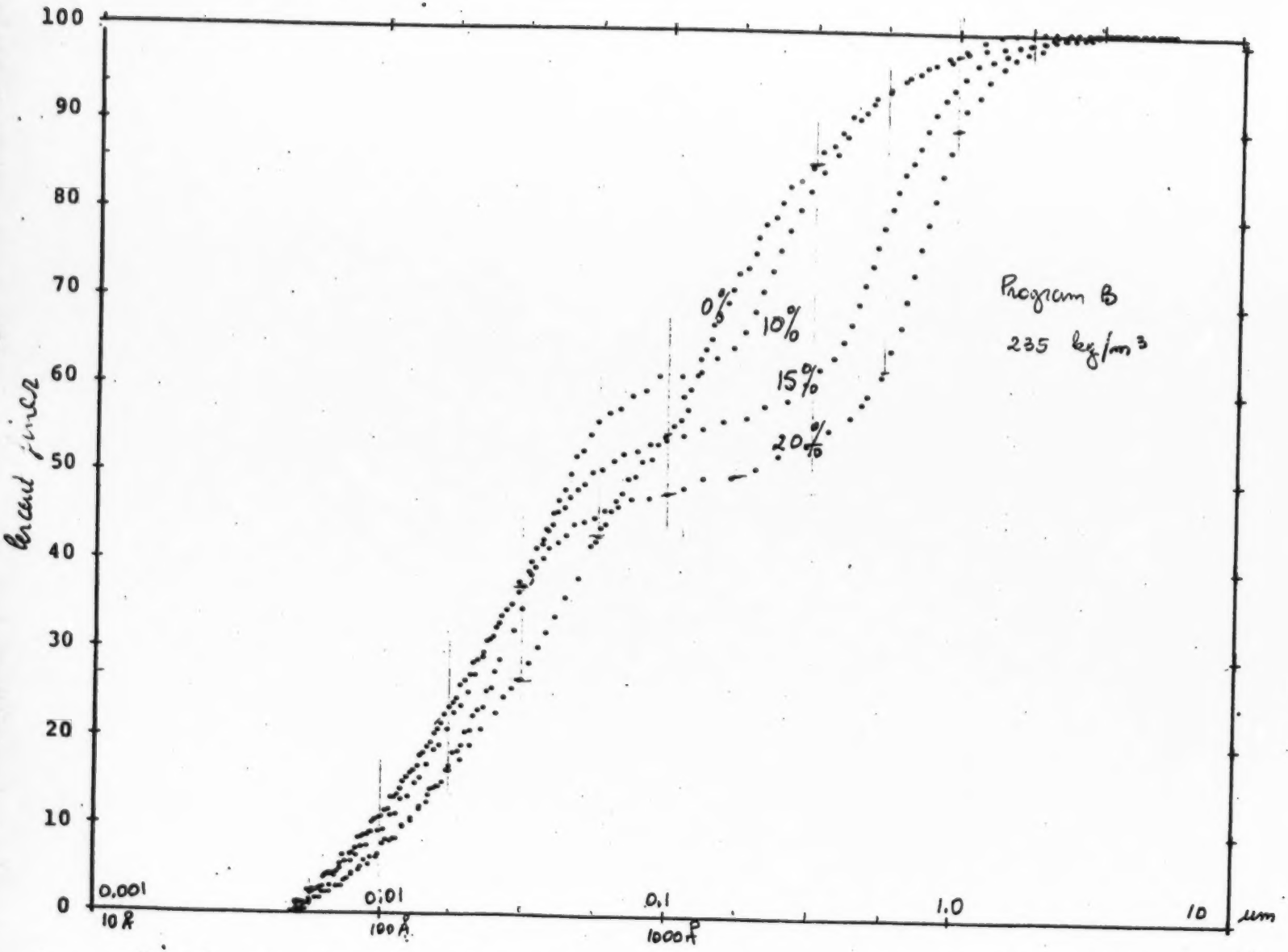


FIGURE 24 PORE SIZE DISTRIBUTION OF THE CONCRETES OF PROGRAM B.

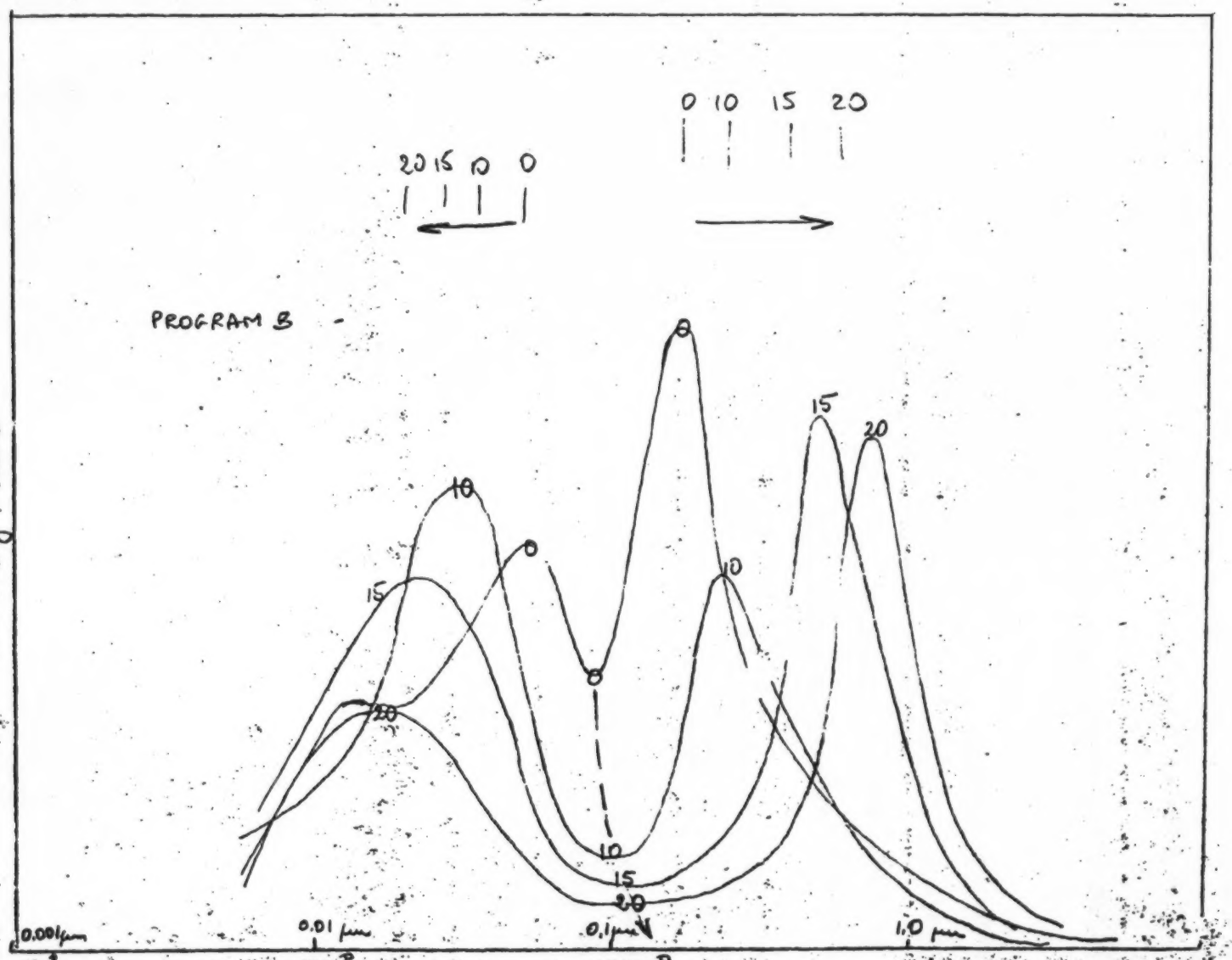


FIGURE 25 COMPARISON OF THE PORE SIZE DISTRIBUTION OF THE CONCRETES OF

Moreover the curves corresponding to the mixes that contain C.S.F. are reaching the X-axis with a certain slope indicating once more that there exist pores finer than 50 Å when C.S.F. is added in the mix.

Comparison of the pore size distribution of A-10 and B-0 concretes (Figures 26 - 27)

All along our research it has been mentioned that from a mechanical point of view the two concretes A-10 and B-0 were equivalent; same compressive strength at 28 d and 91 d and same young modulus at 28 d. It is interesting to compare the pore size distribution of these two concretes.

Below 800 Å the pore size distribution of these 2 concretes is exactly the same while above this value there is a big difference.

Considering the pore range 800 Å - 4000 Å, in concrete B we observe a maximum in the histogram, while a minimum is observed for the concrete A-10.

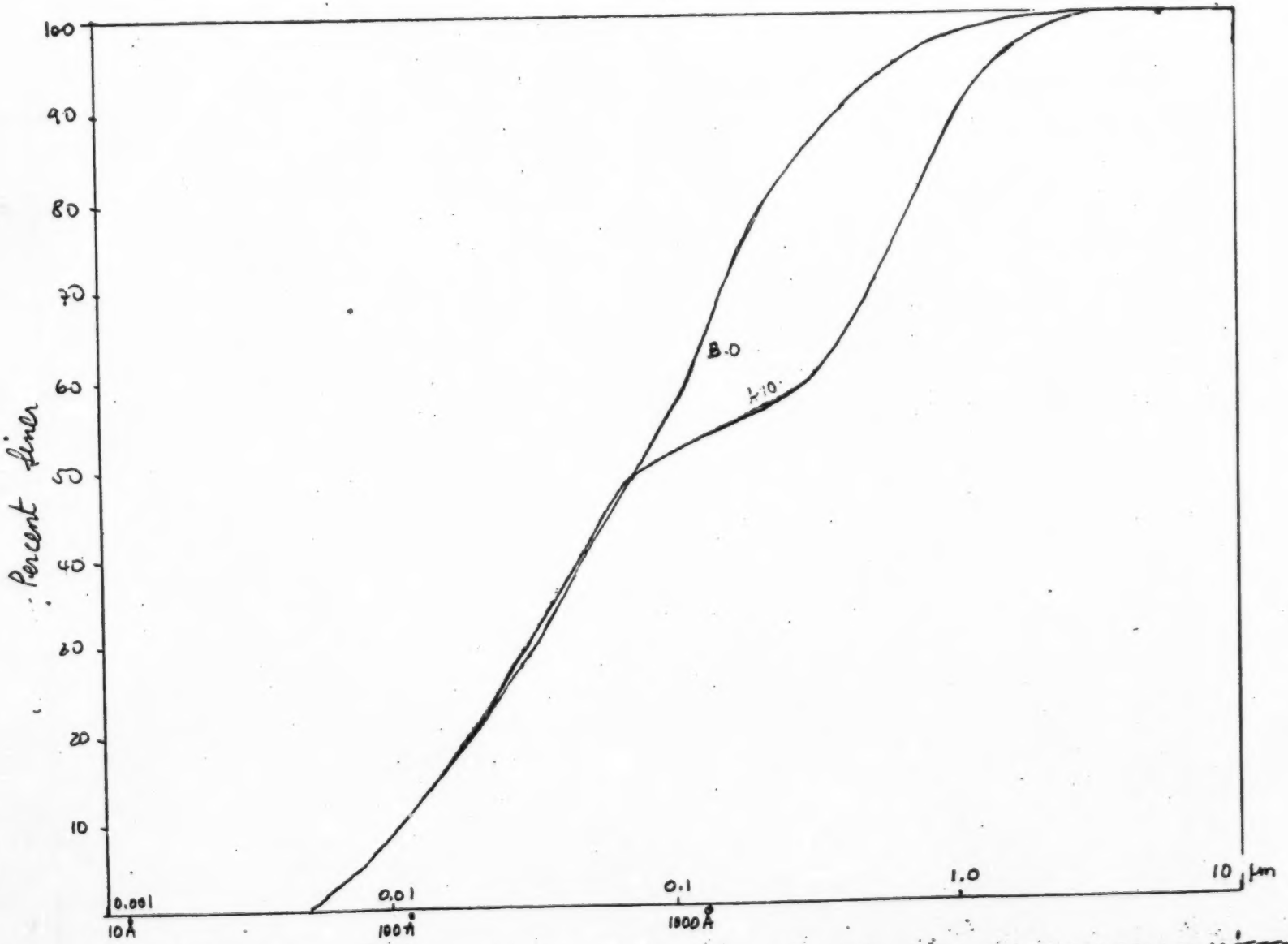
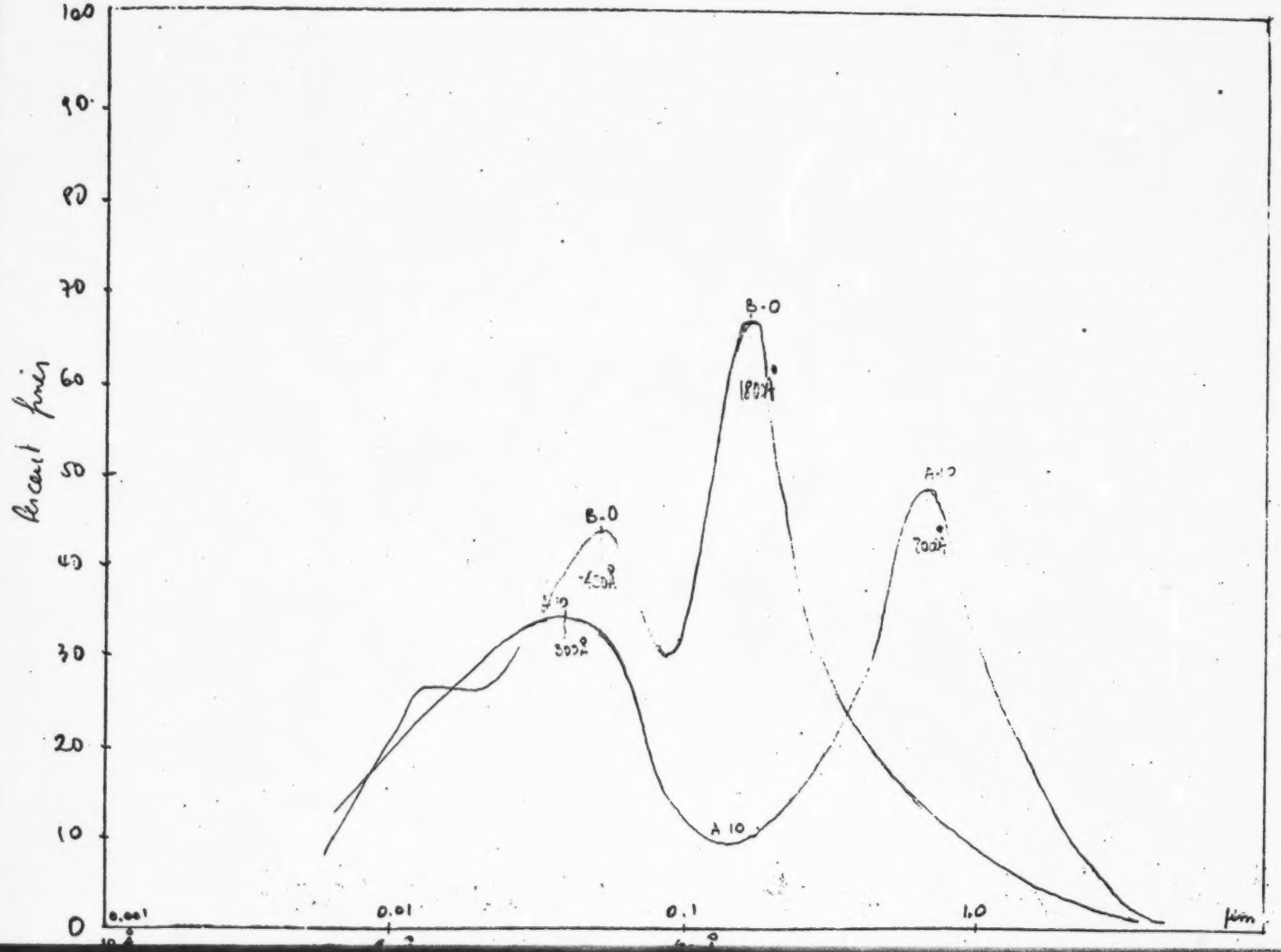


FIGURE 26 COMPARISON OF THE PORE SIZE DISTRIBUTION OF A-10 AND B-0 CONCRETES


100
90
80
70
60
50
40
30
20
10
0
Percent finer
B-O
B-O
A-10
A 10
0.001
0.01
0.1
1.0
mm

POOR

QUALITY

ORIGINAL